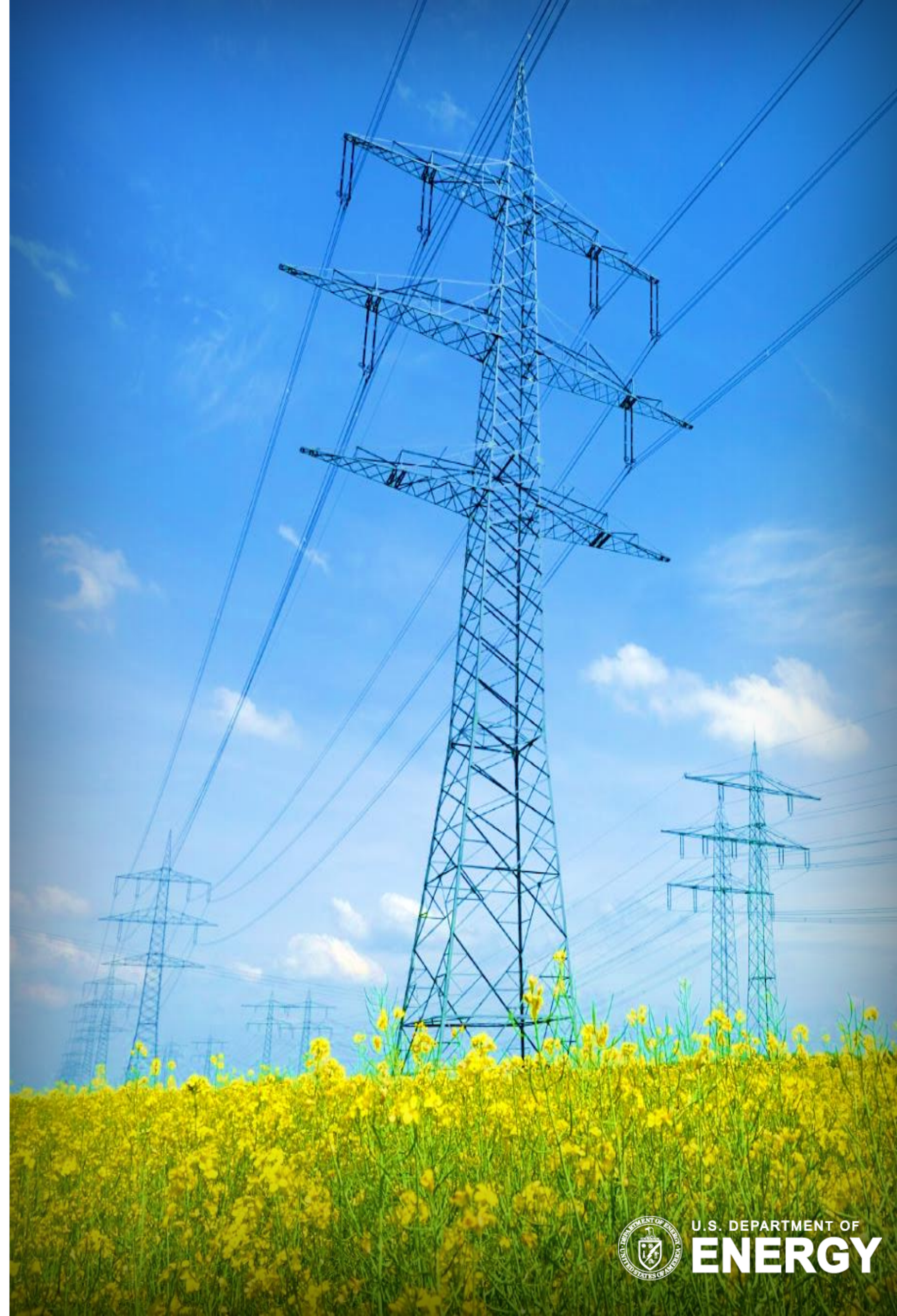
Ultrasonic Seismic Wave Elastic Moduli and Attenuation, Petrophysical Models and Work Flows for Better Subsurface Imaging Related to Monitoring of Sequestrated Supercritical CO_2 and Geothermal Energy Exploration

Presented by William Harbert
NRAP Webinar Series #3

January 10, 2017

NATIONAL ENERGY TECHNOLOGY LABORATORY



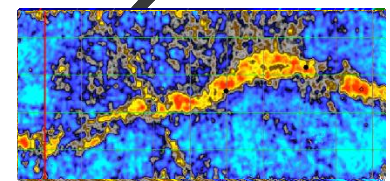
Presentation: Seismic Wave Elastic Moduli and Attenuation, Petrophysical Models and Work Flows for Better Subsurface Imaging Related to Monitoring of Sequestrated Supercritical CO_2 and Geothermal Energy Exploration

- William Harbert, University of Pittsburgh
- Daniel Delaney, Dawson Geophysical
- Alan J Mur, Ikon Science
- Christopher Purcell, Nexen CNOOC Ltd.
- Erich Zorn, ORISE NETL-Pittsburgh
- Yee Soong, NETL Pittsburgh
- Dustin Crandall, NETL Morgantown
- Igor Haljasmaa, AECOM NETL-Pittsburgh

A View of Seismic Acquisition Evolution

Technology ‘S-curves’ in Seismic imaging

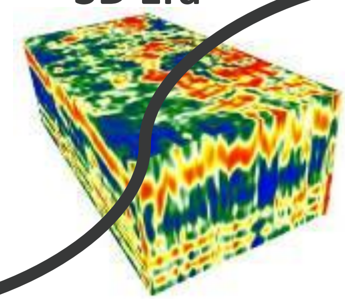
Full-wave Era



2007

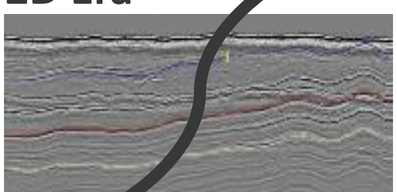
2000’s

3D Era



1970’s

2D Era



1920’s

Characteristics of the Full-wave Era

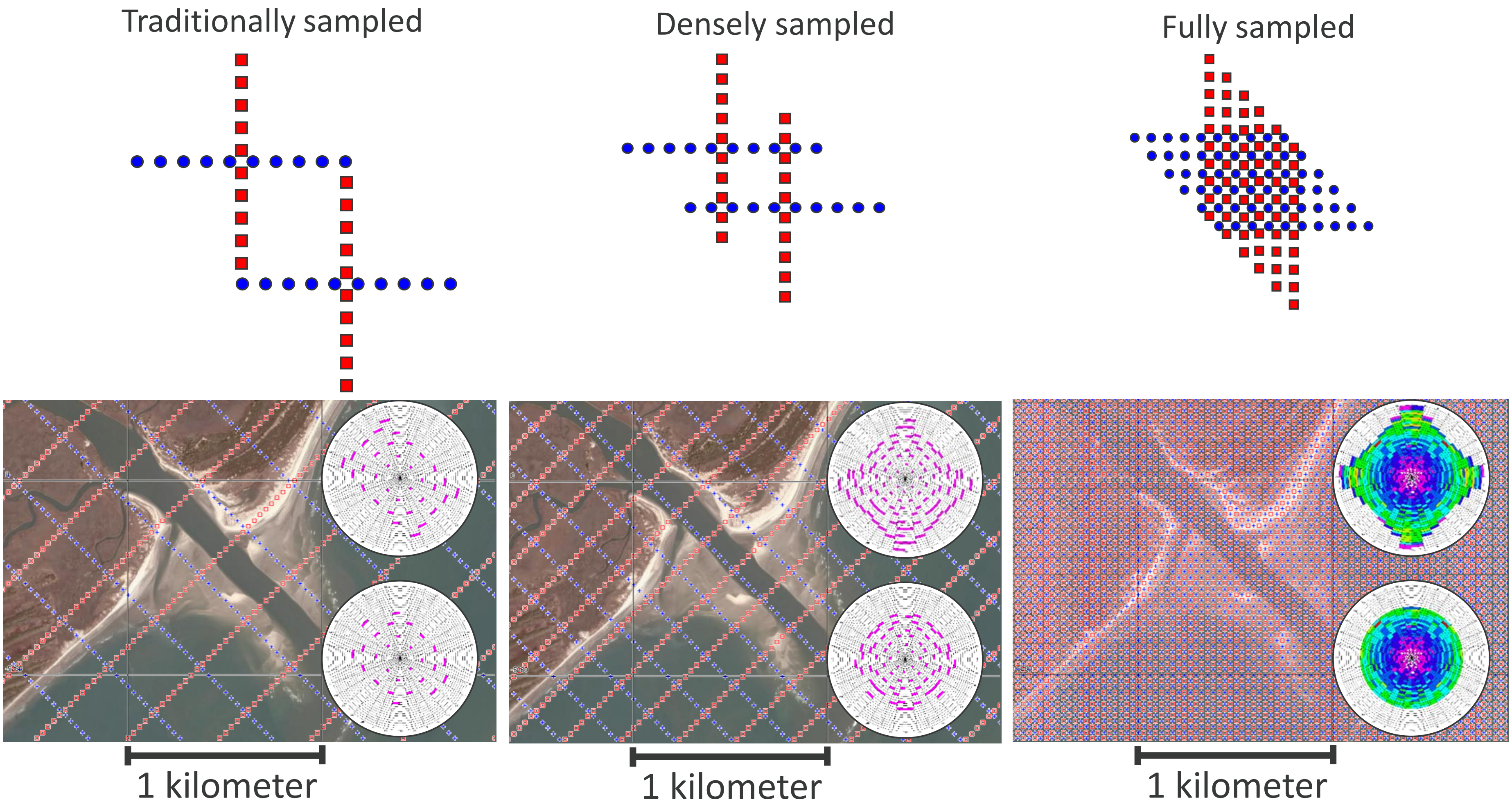
- Measurement of both P- and S-waves
- Densely sampled data
- Game-changing recording systems
- Integrated acquisition methodologies
- Next-generation imaging techniques

Anticipated Results

- Improved operational productivity
- Enhanced QHSE performance
- Higher resolution images
- Stratigraphic variables
- Lithology determination
- Fracture definition
- Complex structure
- Fluid characterization & tracking

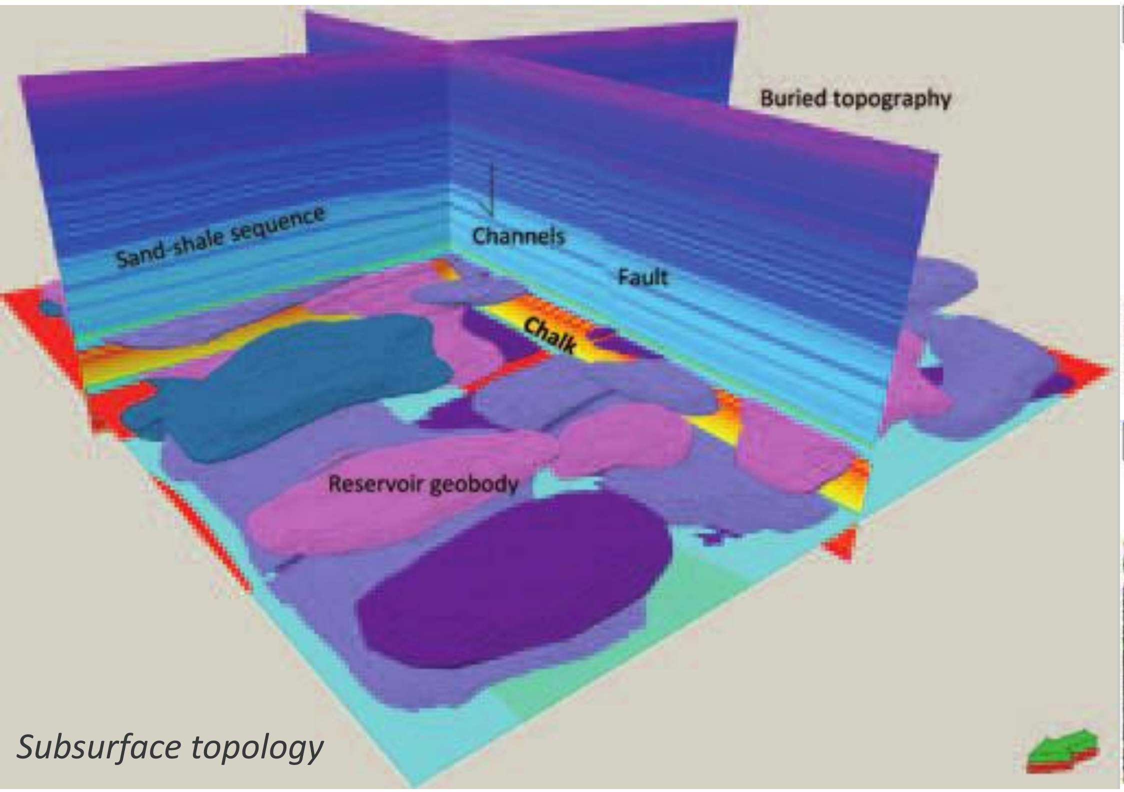
Courtesy of IKON

Seismic sampling and the importance of core and well log calibration

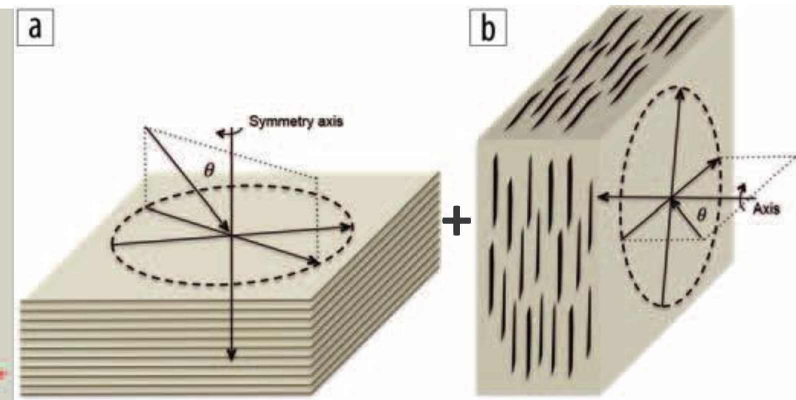


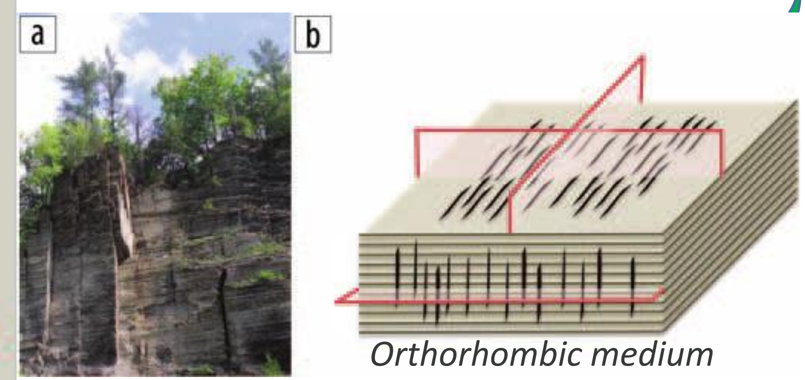
Courtesy of IKON

VTI / HTI Anisotropy

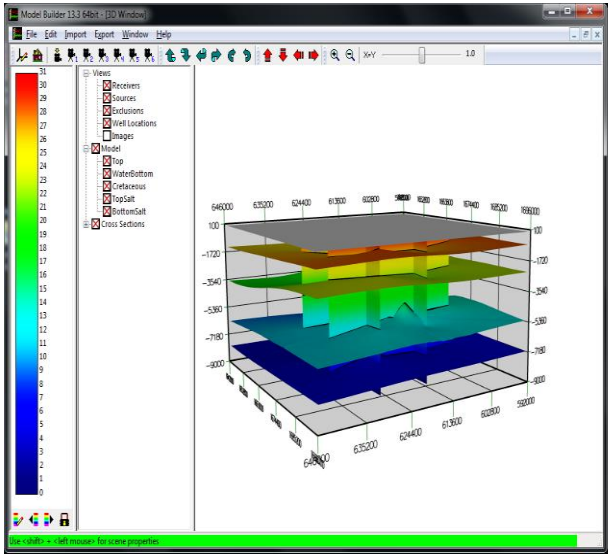


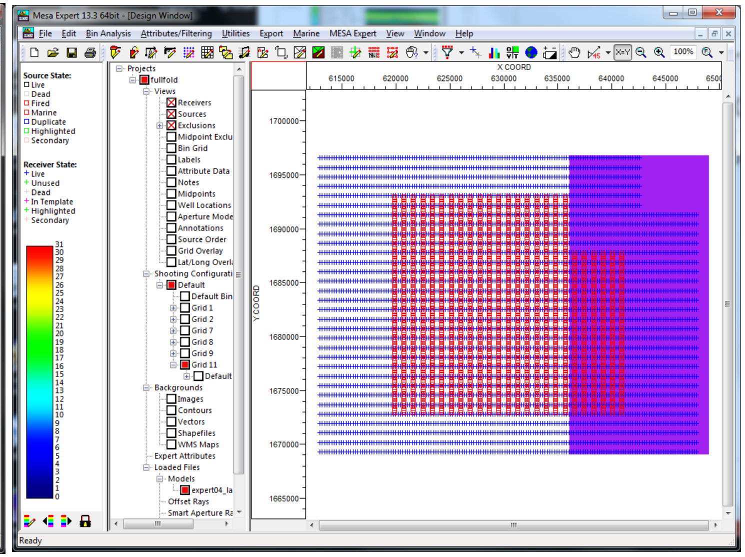
A vertical transversely isotropic (VTI) medium + A horizontal transversely isotropic (HTI) medium

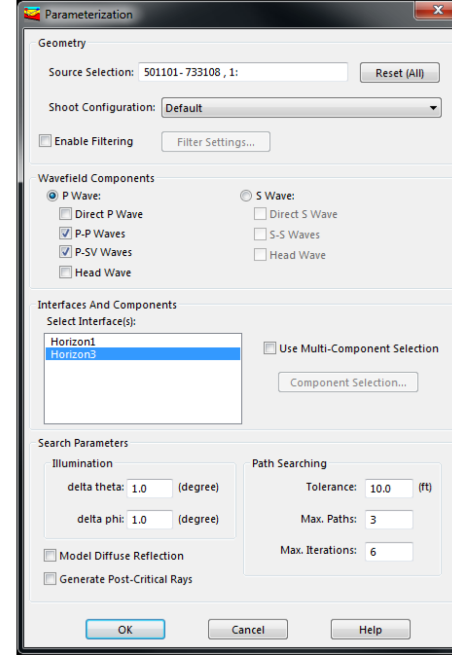




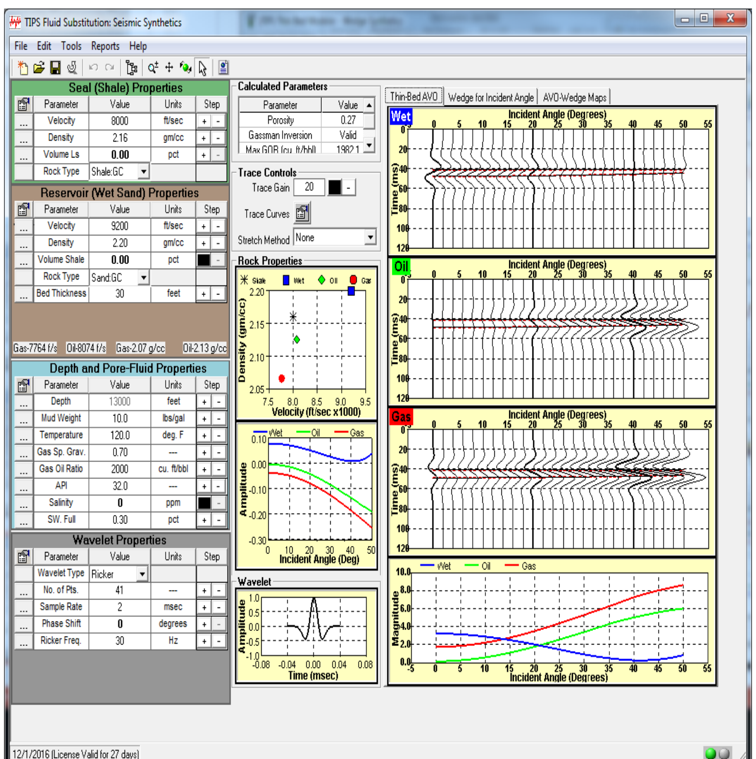
From: TLE, Elastic anisotropy in SEAM Phase II models

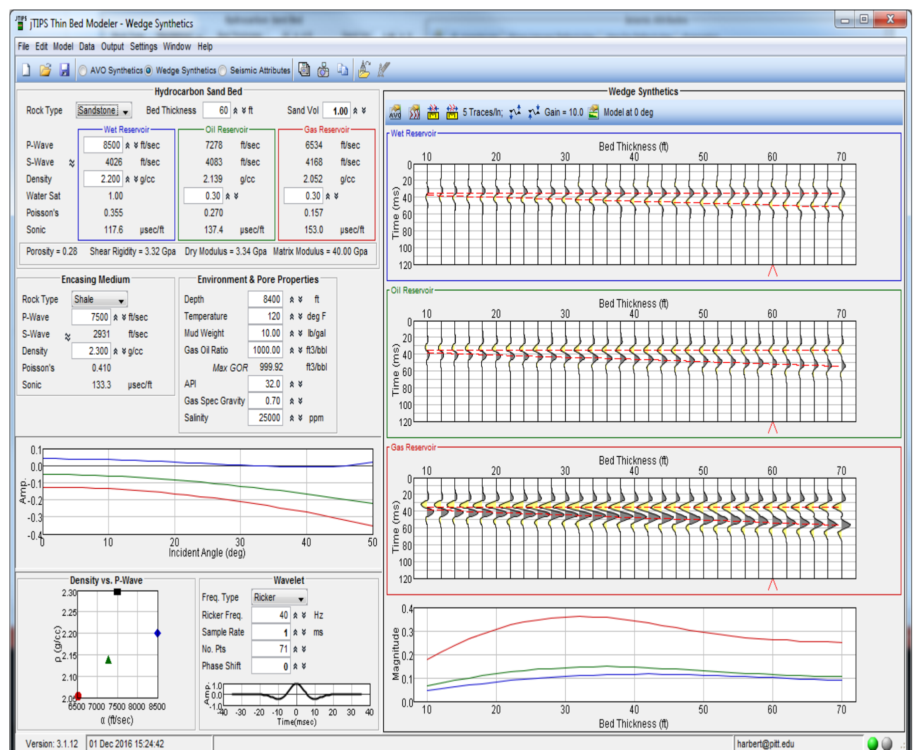




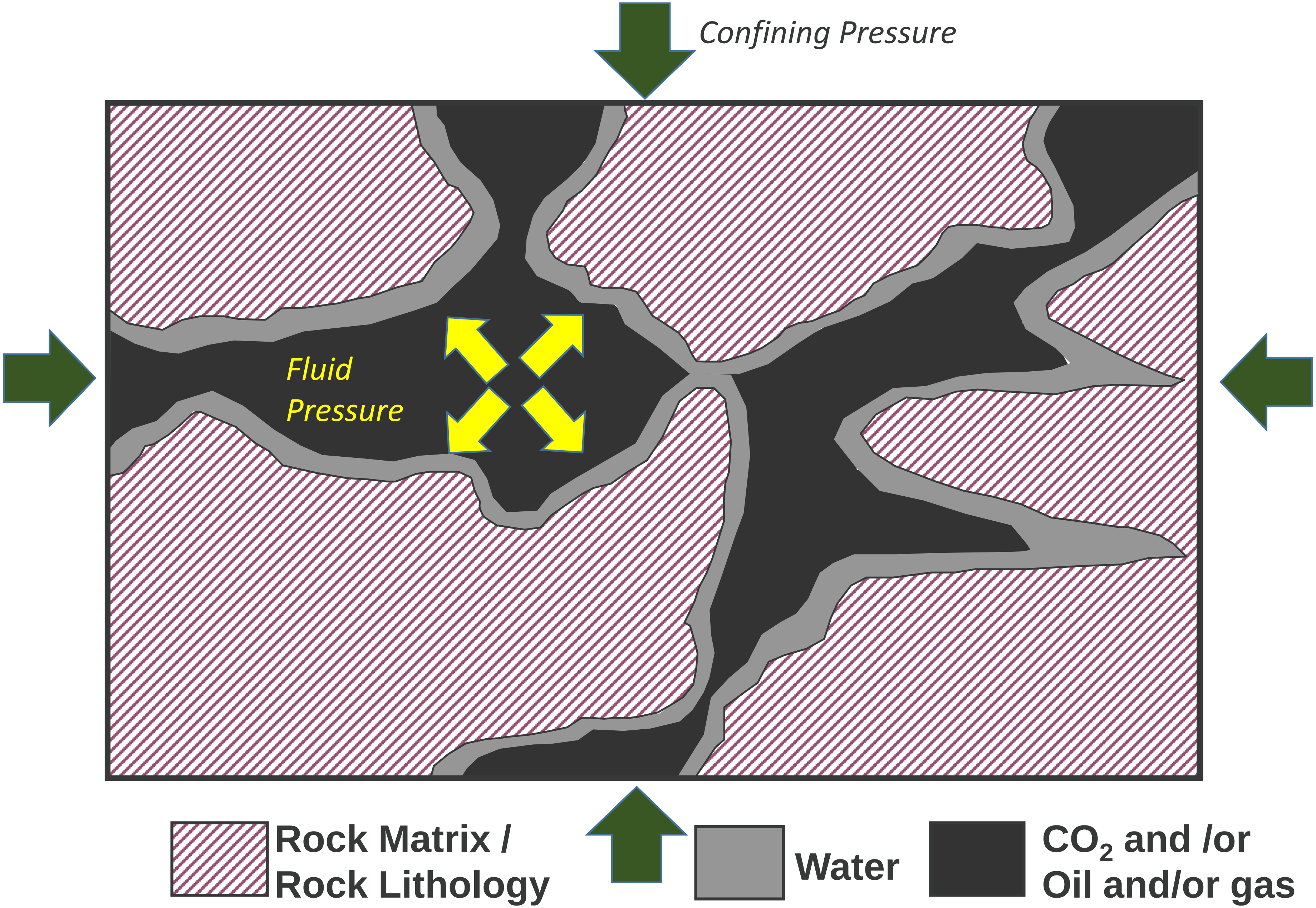


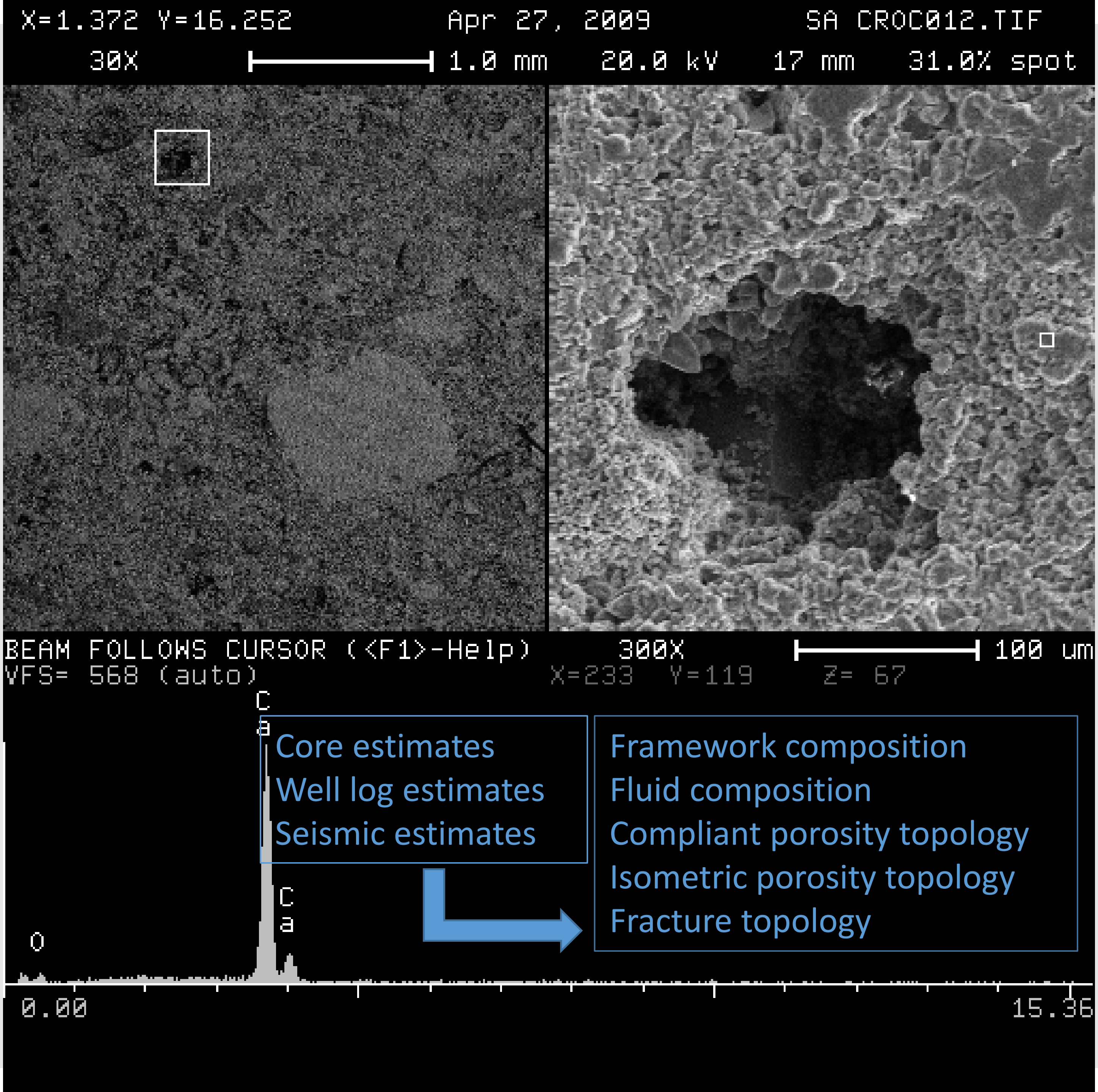
Typical seismic forward modeling





ROCK MATRIX AND PORE SPACE

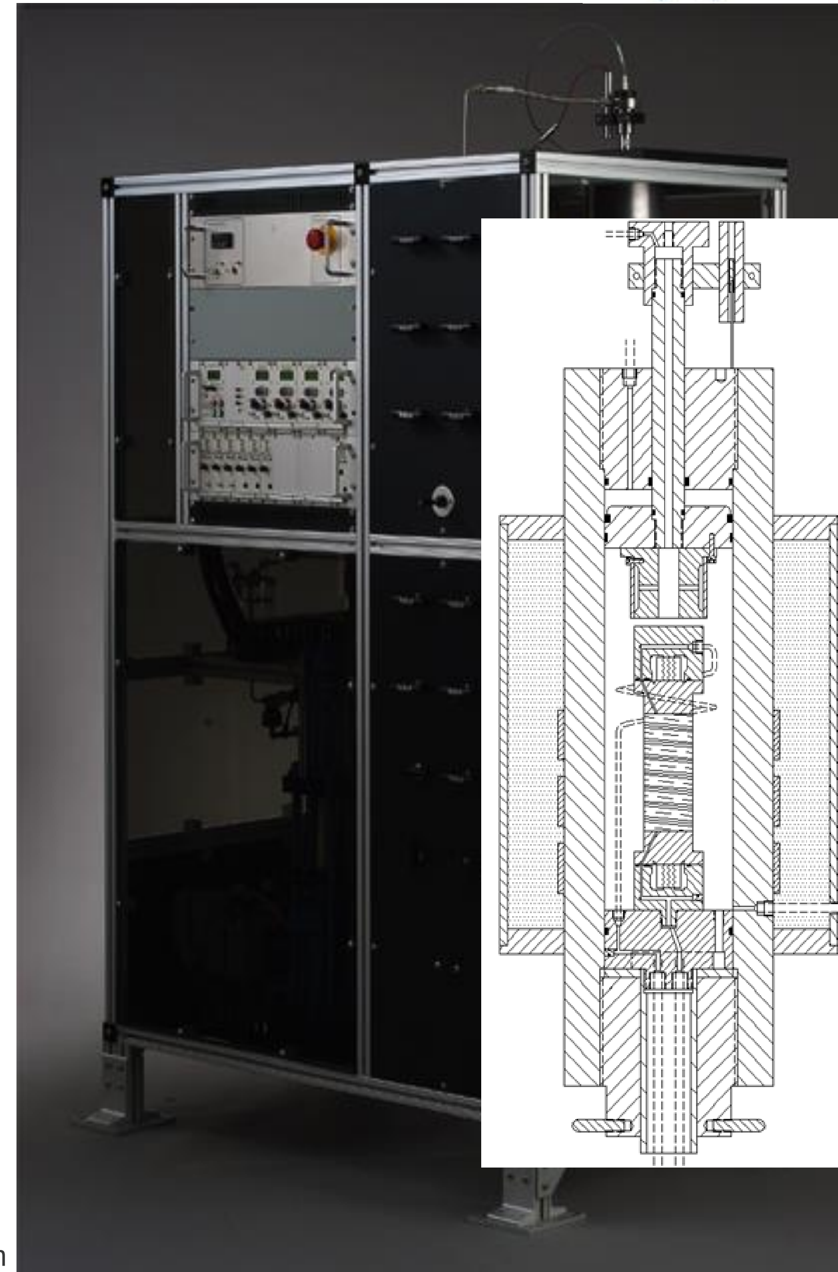



X=1.372 Y=16.252
Apr 27, 2009
SA CROC012.TIF
30X
1.0 mm
20.0 kV
17 mm
31.0% spot
BEAM FOLLOWS CURSOR (<F1>-Help)
VFS= 568 (auto)
300X
100 um
X=233 Y=119
Z= 67
Ca
Ca
O
0.00
15.36
Core estimates
Well log estimates
Seismic estimates
Framework composition
Fluid composition
Compliant porosity topology
Isometric porosity topology
Fracture topology

Experimental Setup

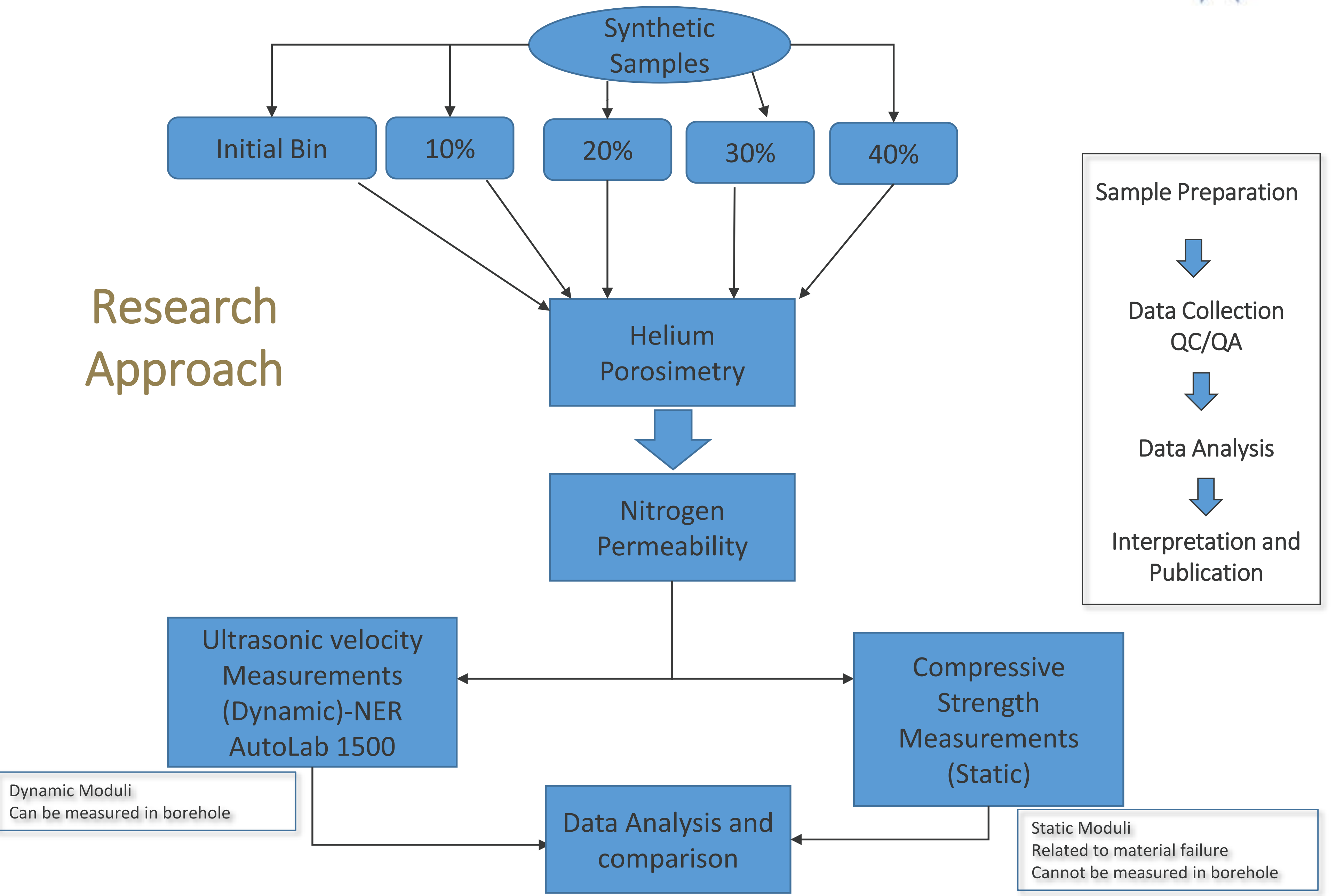
Ultrasonic velocity Measurements (Dynamic)-NER AutoLab 1500

Porosimetry



www.NER.com

Research Approach



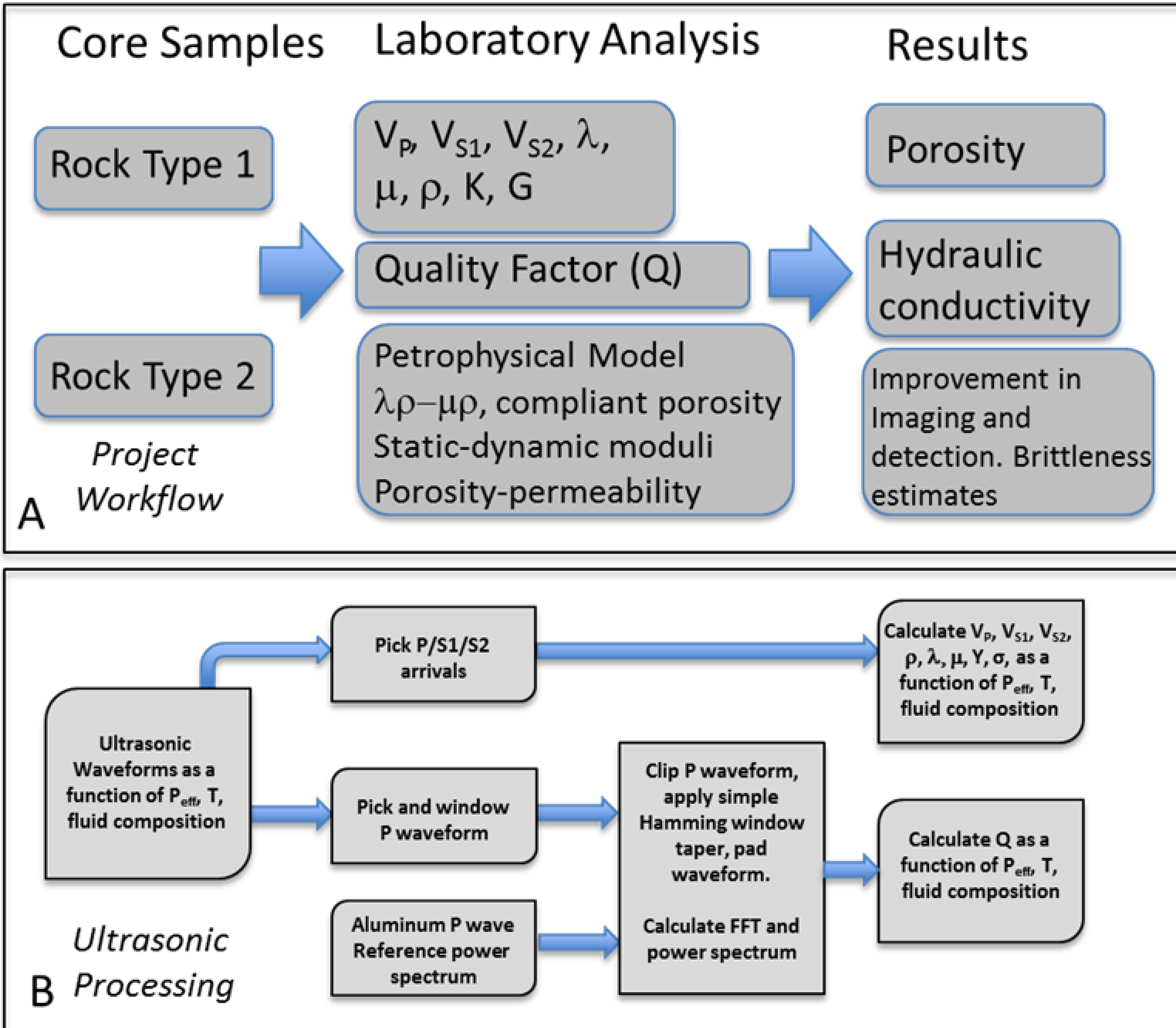

Core Samples
Laboratory Analysis
Results
Rock Type 1
Rock Type 2
V_P, V_{S1}, V_{S2}, λ, μ, ρ, K, G
Quality Factor (Q)
Petrophysical Model
λρ−μρ, compliant porosity
Static-dynamic moduli
Porosity-permeability
Porosity
Hydraulic conductivity
Improvement in Imaging and detection. Brittleness estimates
Project Workflow
A
Ultrasonic Waveforms as a function of P_{eff}, T, fluid composition
Pick P/S1/S2 arrivals
Calculate V_P, V_{S1}, V_{S2}, ρ, λ, μ, Y, σ, as a function of P_{eff}, T, fluid composition
Pick and window P waveform
Aluminum P wave Reference power spectrum
Clip P waveform, apply simple Hamming window taper, pad waveform.
Calculate FFT and power spectrum
Calculate Q as a function of P_{eff}, T, fluid composition
Ultrasonic Processing
B

Figure 1

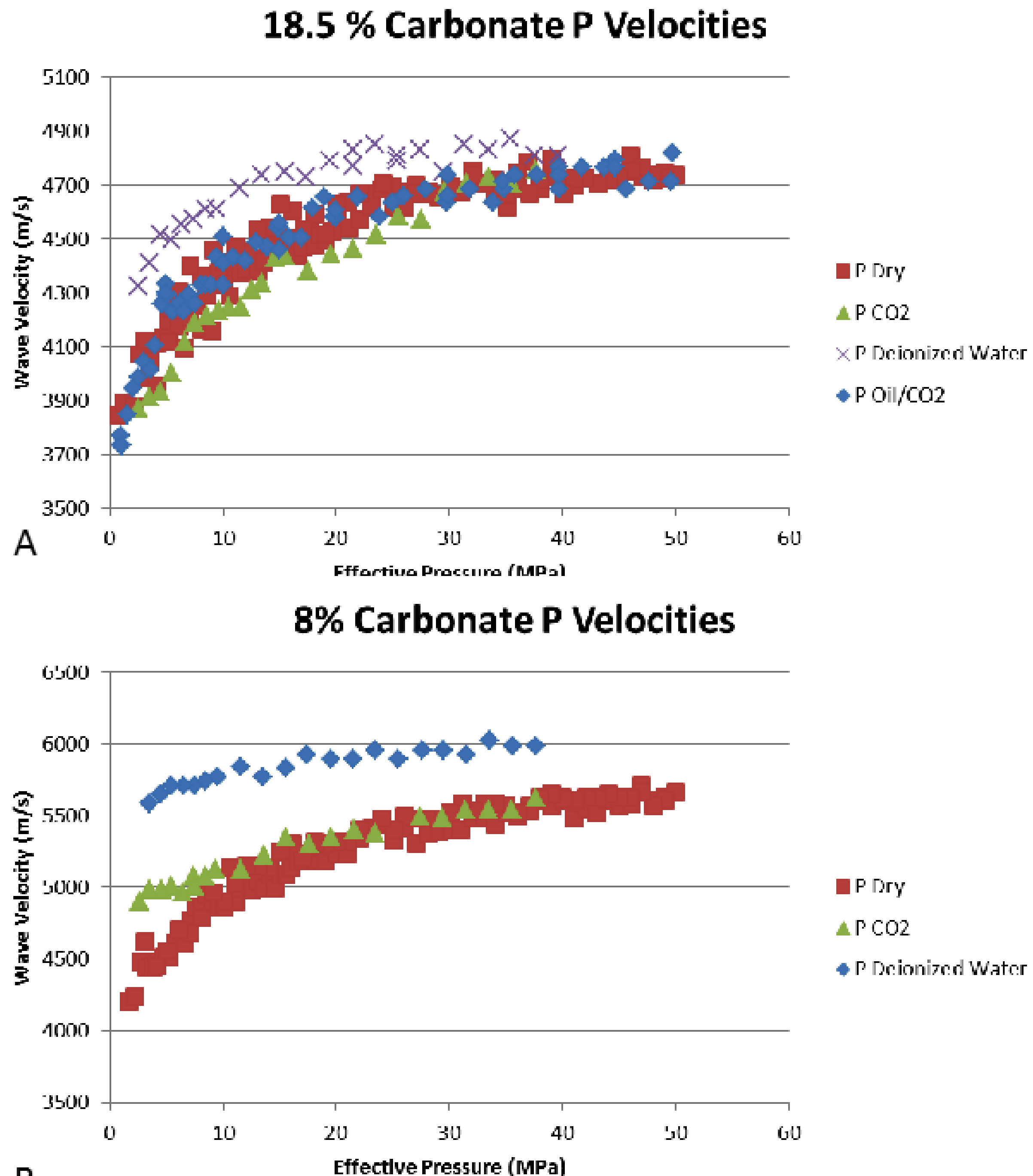

18.5 % Carbonate P Velocities
Wave Velocity (m/s)
5100
4900
4700
4500
4300
4100
3900
3700
3500
0
10
20
30
40
50
60
Effective Pressure (MPa)
A
P Dry
P CO2
P Deionized Water
P Oil/CO2
8% Carbonate P Velocities
Wave Velocity (m/s)
6500
6000
5500
5000
4500
4000
3500
0
10
20
30
40
50
60
Effective Pressure (MPa)
B
P Dry
P CO2
P Deionized Water

Figure 6

Biot-Gassmann fluid replacement equation in Lamé terms

Biot-Gassmann Equation:
K is bulk modulus,
"sat" is saturated rock, ϕ is porosity

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_{solid}}\right)^2}{\left(1 - \phi - \frac{K_{dry}}{K_{solid}}\right)(K_{solid})^{-1} + \left(\frac{\phi}{K_{fluid}}\right)}$$

Approximation to Biot-Gassmann Equation in Lamé terms

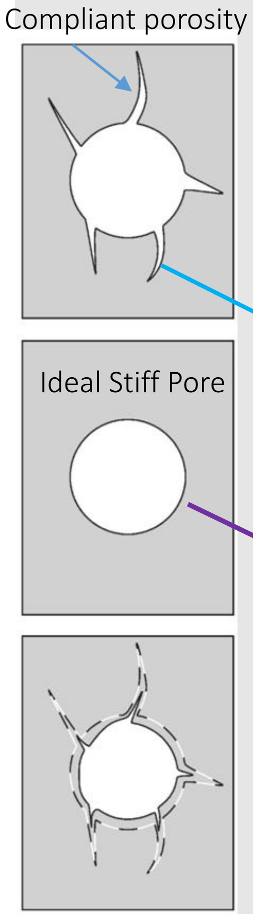
Assuming $\mu_{dry} = \mu_{sat}$ substitute $\Delta\lambda = \lambda_{sat} - \lambda_{dry}$

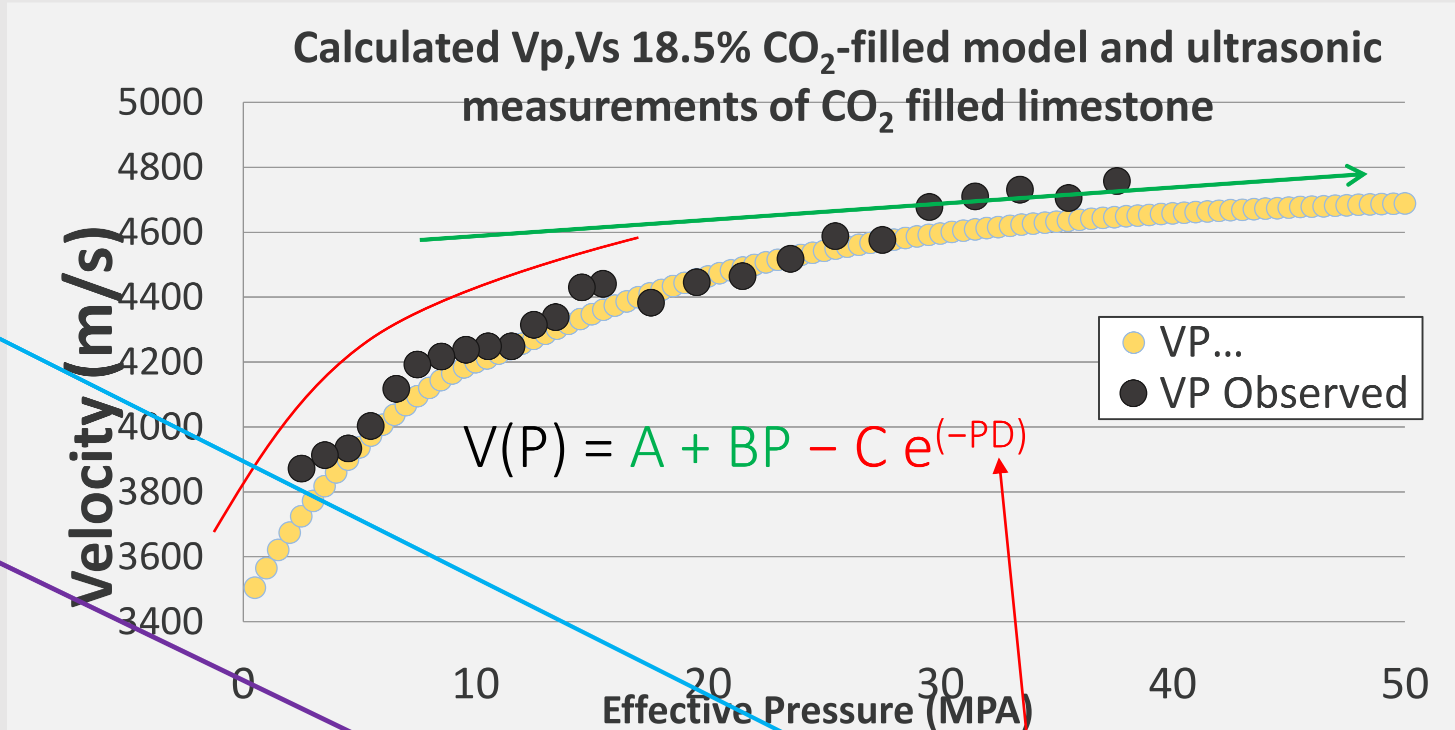
$$\Rightarrow \Delta\lambda \approx \frac{\lambda_{fluid}}{\phi}\left(1 - \frac{K_{dry}^2}{K_{solid}^2}\right)$$

Where $\Delta\lambda$ is the "fluid term" related to $\rho\Delta\lambda$ "pore space modulus"
(from Hedlin, Russell, Hilterman and Lines 2003)

Observations:

- Low $\Delta\lambda$ sensitivity for high modulus (K_{solid}) rock e.g. Carbonates
- λ can never be negative as λ_{fluid}, ϕ, K_{dry}^2 and K_{solid}^2 are always positive





$$K_{dry}(P_{eff}) = K_{dryS}\left[1 + \theta_s\left(\frac{1}{K_{dryS}} - \frac{1}{K_0}\right)P_{eff} - \phi_{c0}\theta_c e^{(-\theta_c P_{eff}/K_{dryS})}\right]$$

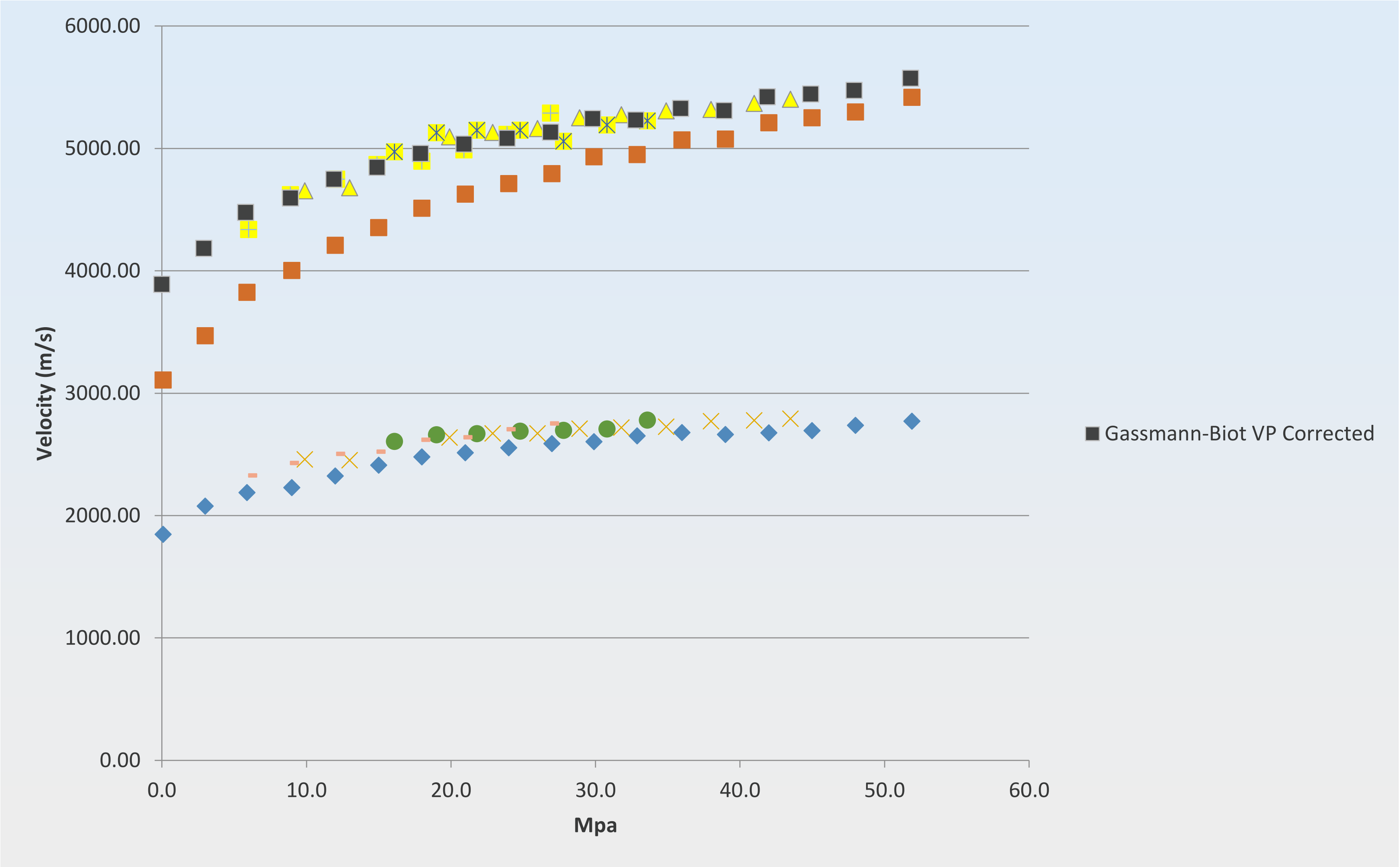
$$\mu_{dry}(P_{eff}) = \mu_{dryS}\left[1 + \theta_{s\mu}\left(\frac{1}{K_{dryS}} - \frac{1}{K_0}\right)P_{eff} - \phi_{c0}\theta_c e^{(-\theta_c P_{eff}/K_{dryS})}\right]$$

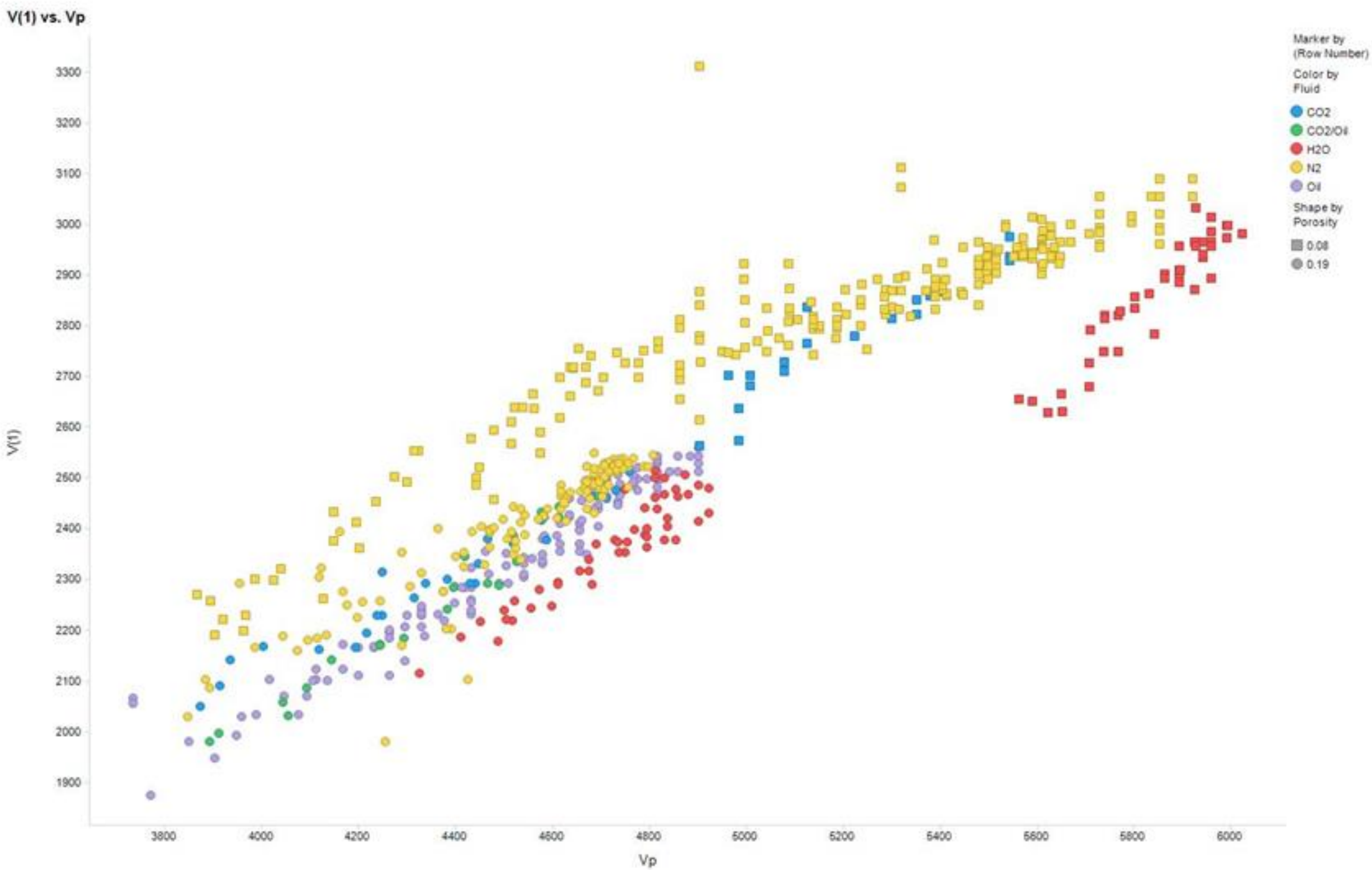
CO_2 ρ and K from NIST

Shapiro 2005

This slide courtesy Dr. Alan Mur, IKON Science

Corrected Rock Physics Model





V(1) vs. Vp
V(1)
Vp
3300
3200
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200
2100
2000
1900
3800
4000
4200
4400
4600
4800
5000
5200
5400
5600
5800
6000
Marker by (Row Number)
Color by Fluid
CO2
CO2/Oil
H2O
N2
Oil
Shape by Porosity
0.08
0.19

Figure 7

Who was Lamé and what is the physical significance of his parameters Lambda (λ) and Mu (μ) ?

- Gabriel Lamé (1795-1870): French engineer, mathematician and elastician.
- Introduced λ and μ in 1828, named after himself, in a series of lectures titled:

“Mémoire sur l’équiulibre intérieur des corps solides homogènes”

- Lamé formulated the modern version of Hooke’s law relating stress to strain in general tensor form, creating the basis for the science of materials, including rocks.
- Interestingly and most notably, only Lamé’s moduli λ and μ appear in Hooke’s law and not Young’s modulus, the bulk modulus, or any other modulus or modulus ratio.

Disclaimer for use of numerous equations that follow:

"If geophysics requires mathematics for its treatment it is the Earth that is responsible not the geophysicist."

from Sir Harold Jeffreys, University of Cambridge

Assertions

- Lamé moduli of rigidity μ and "incompressibility" λ allow the fundamental parameterization of seismic waves used to extract information about rocks in the Earth.
- These parameters link many fields of Earth Science at different scales, from Petroleum Exploration to Earthquake Seismology.
- Other common formulations result in contradictions which are removed by restating equations using Lamé parameters.

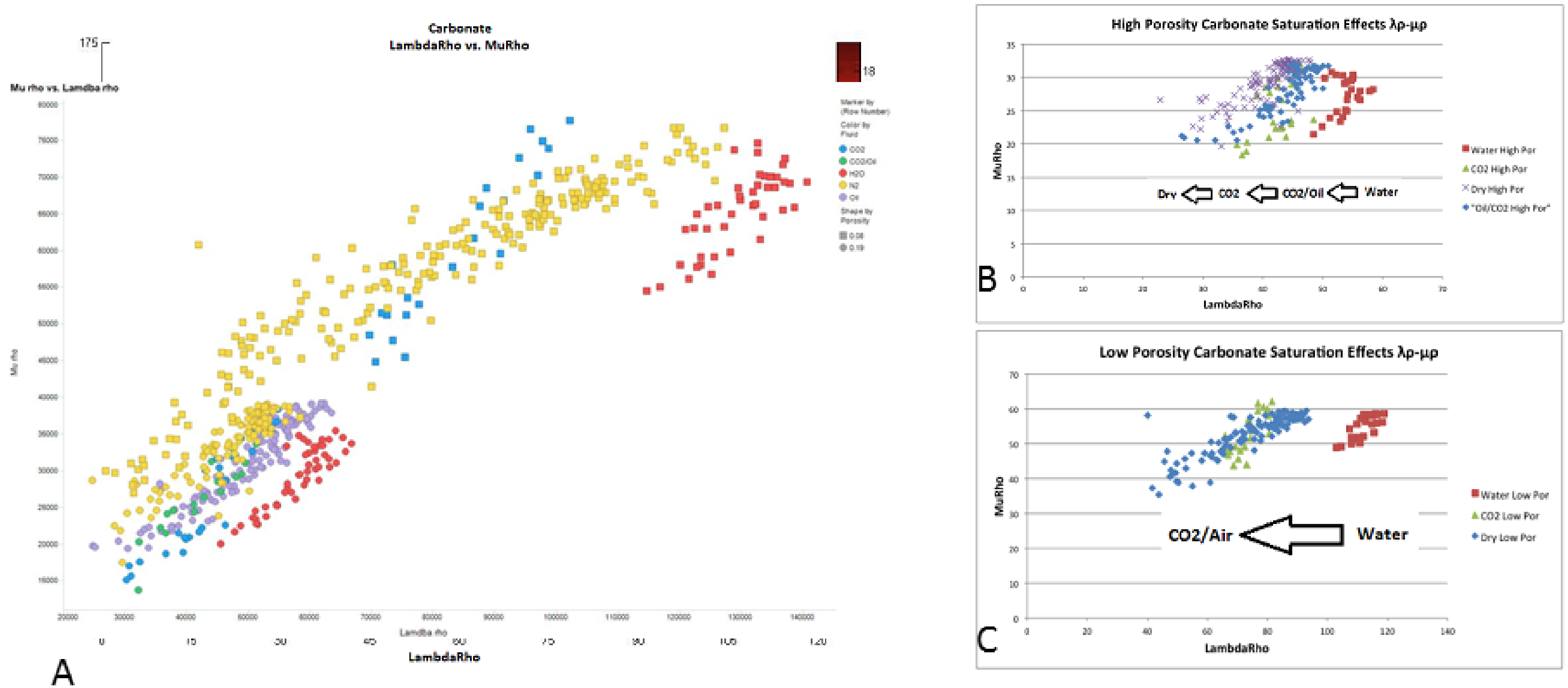
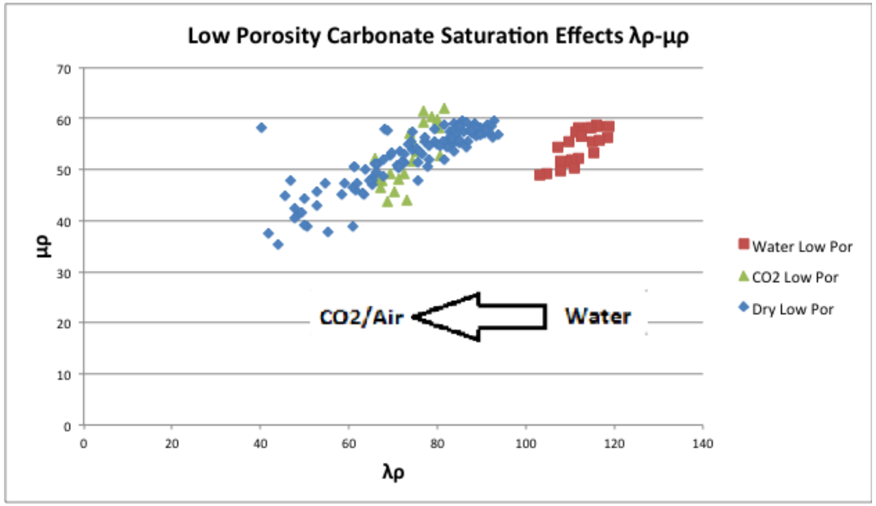
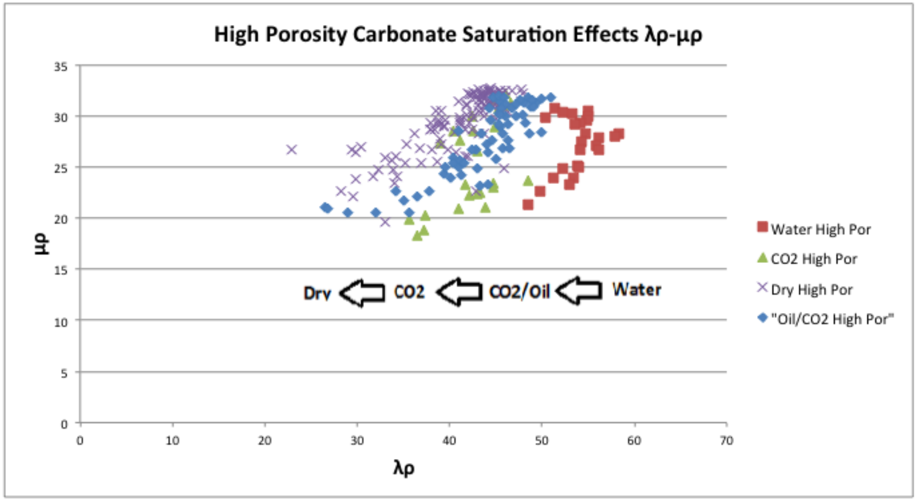


Figure 8

Figure: (A) λρ versus μρ moduli for all carbonate core data. (B) λρ versus μρ moduli for different pore filling phases measured at different effective pressures using the higher porosity carbonate sample. (C) λρ versus μρ moduli for different pore filling phases measured at different effective pressures using the lower porosity carbonate sample.

Fluid saturation in λρ-μρ Coordinates

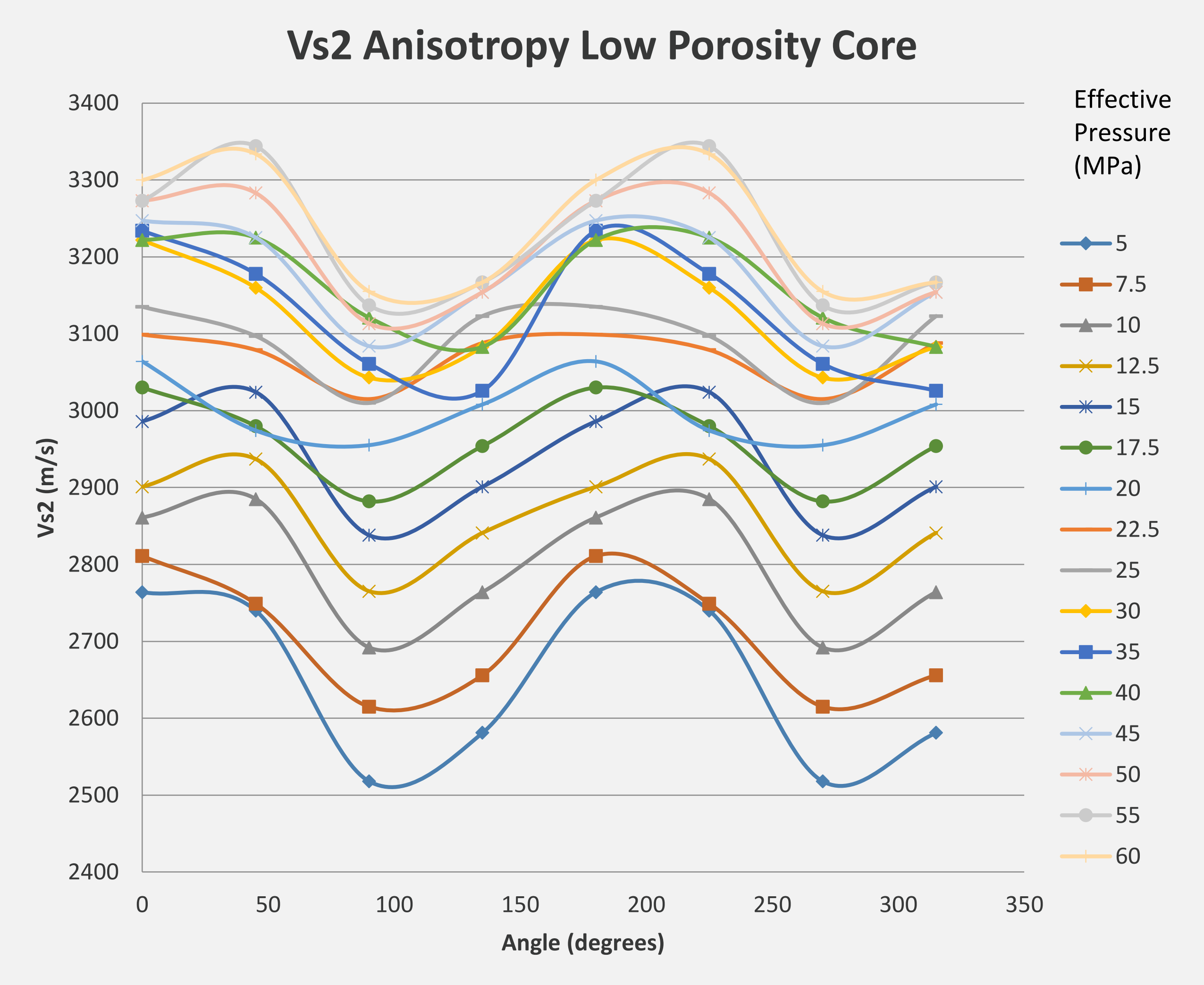




- Lamé moduli of rigidity μ and "incompressibility" λ allow the fundamental parameterization of seismic waves used to extract information about rocks in the Earth.
- The introduction of fluids into the carbonate cores causes a shift in λρ, μρ remains independent of fluid saturation.
- λρ-μρ is dependent on framework characteristics, including porosity, Higher porosity results in lower values for both λρ and μρ.

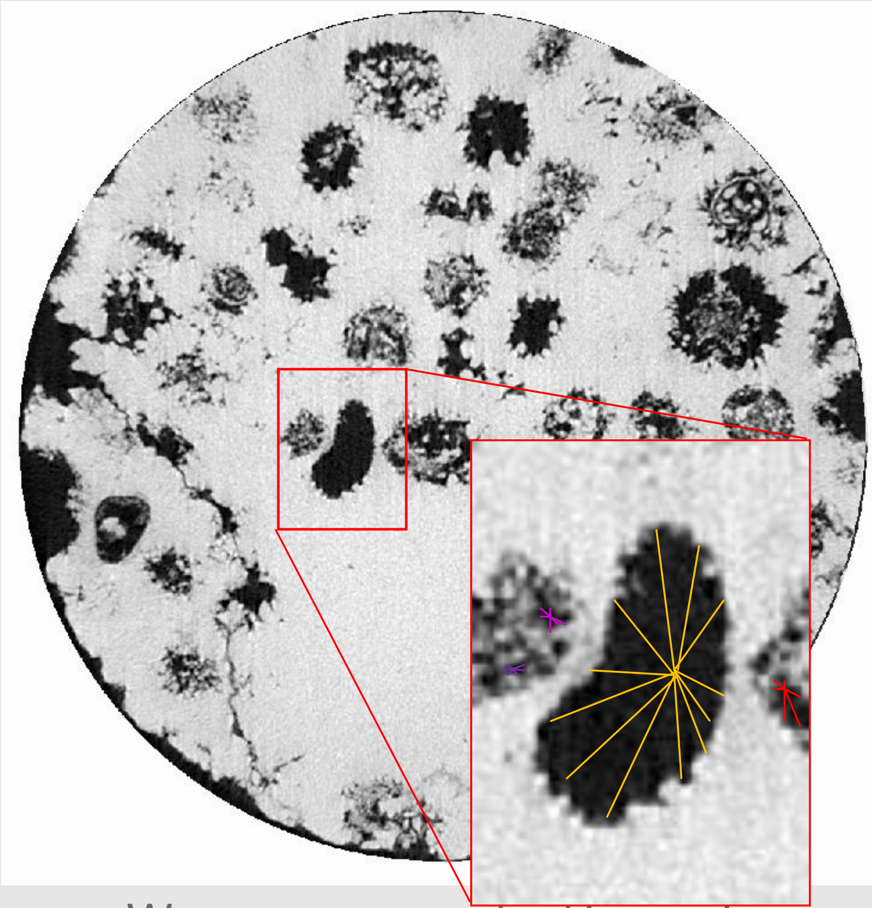
This slide courtesy Mr. Daniel Delaney

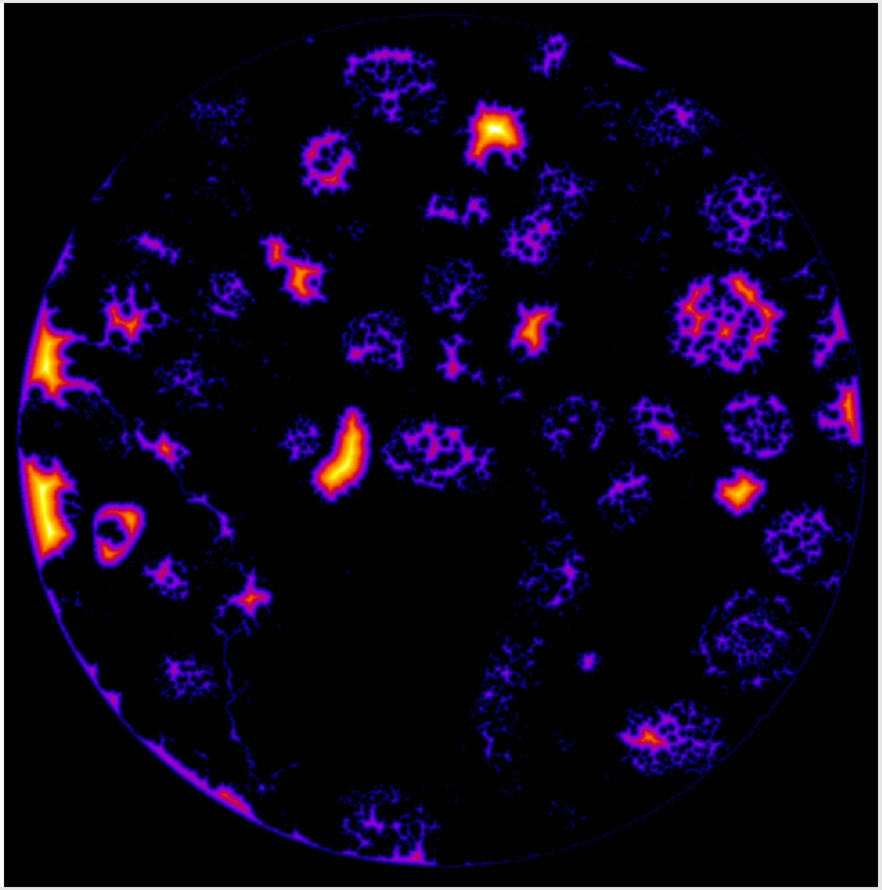
Pore Orientation Effects



Trends in the orientation of pore size groups may cause the anisotropy we observe in sonic velocity measurements. Anisotropic seismic velocity models are not yet popular as they are computer memory intensive (especially in prestack)

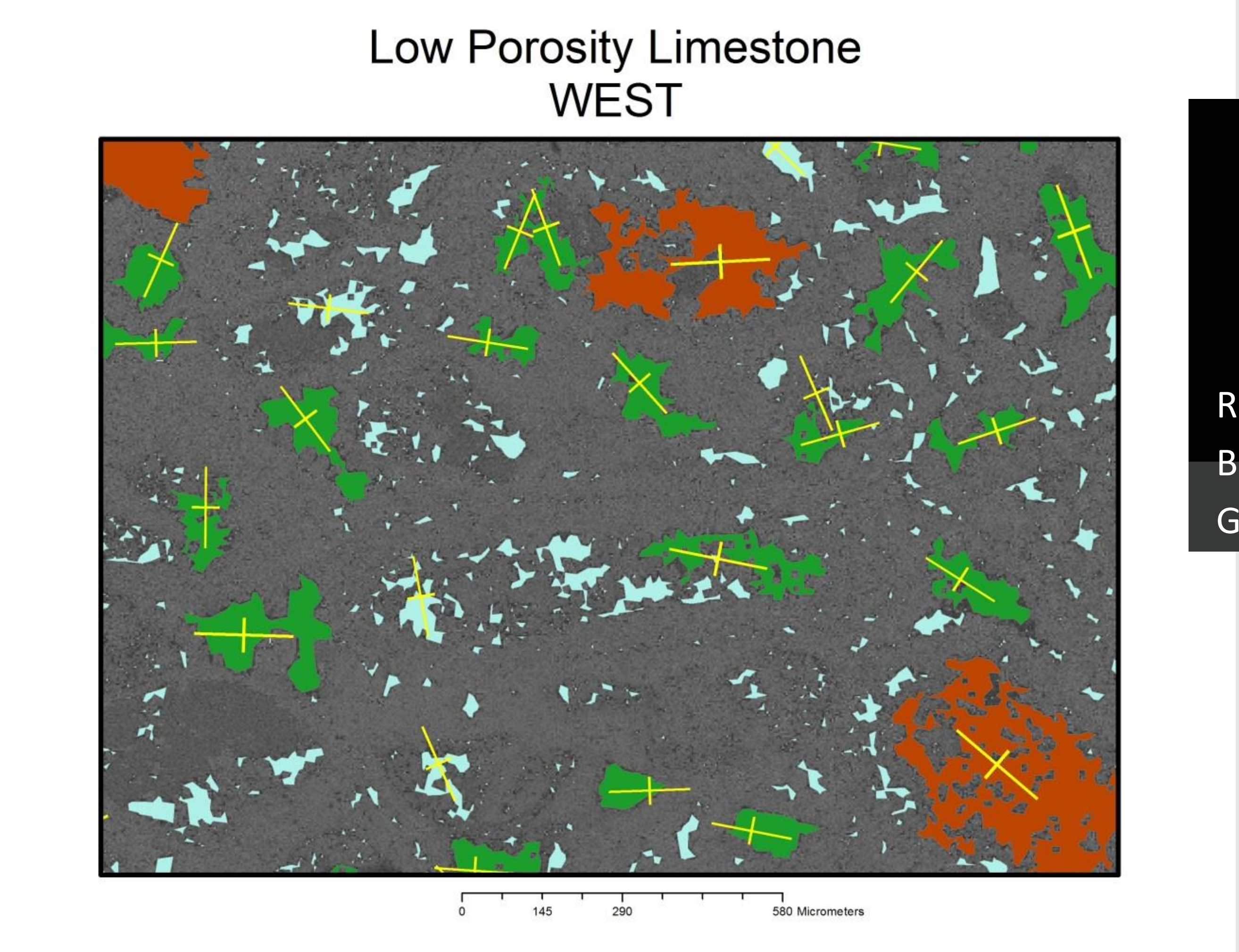
Local Thickness: Cooler colors are compliant porosity (4x sample)

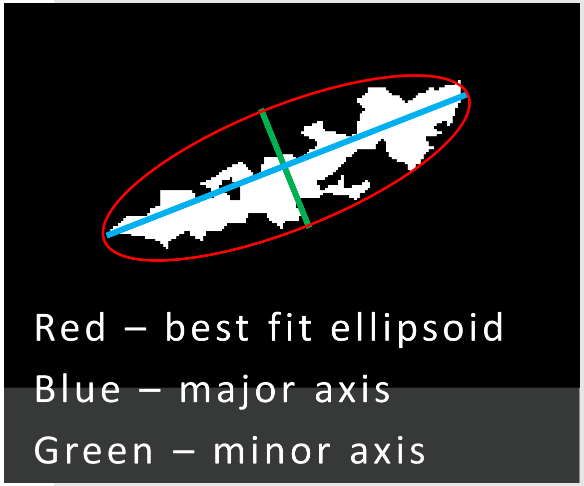




- We can separate the volume of high and low aspect ratio pores to quantify compliant and stiff porosity
- Results can be compared/confirmed by thickness mapping

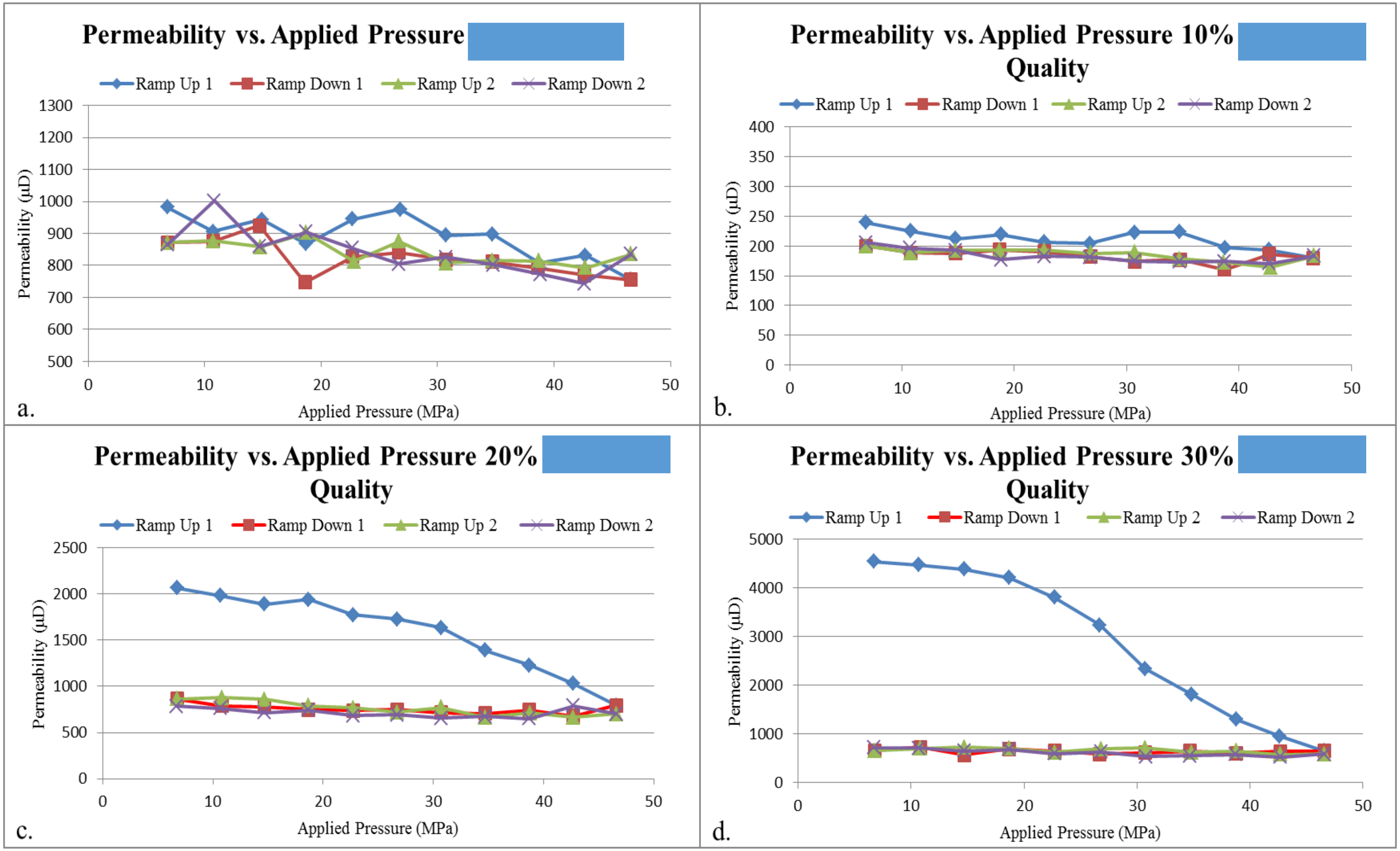
Macro Scale Pore Orientations
SEM





Using three mutually perpendicular, ~40x80cm SEM montages, we described a large number of pores (>10,000 pores per plane) using GIS and image processing.

Effective Pressure Cycling Results – Permeability



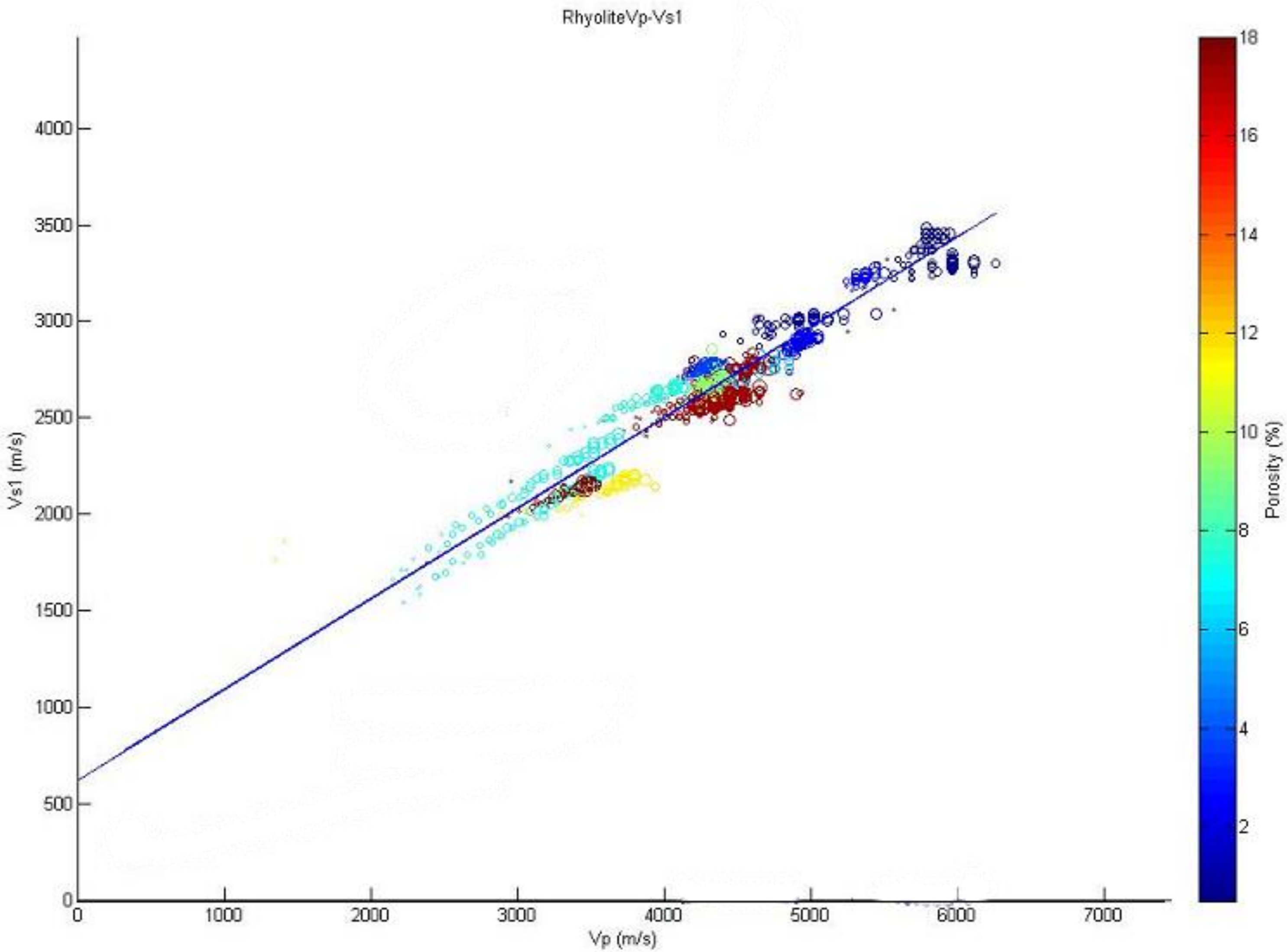
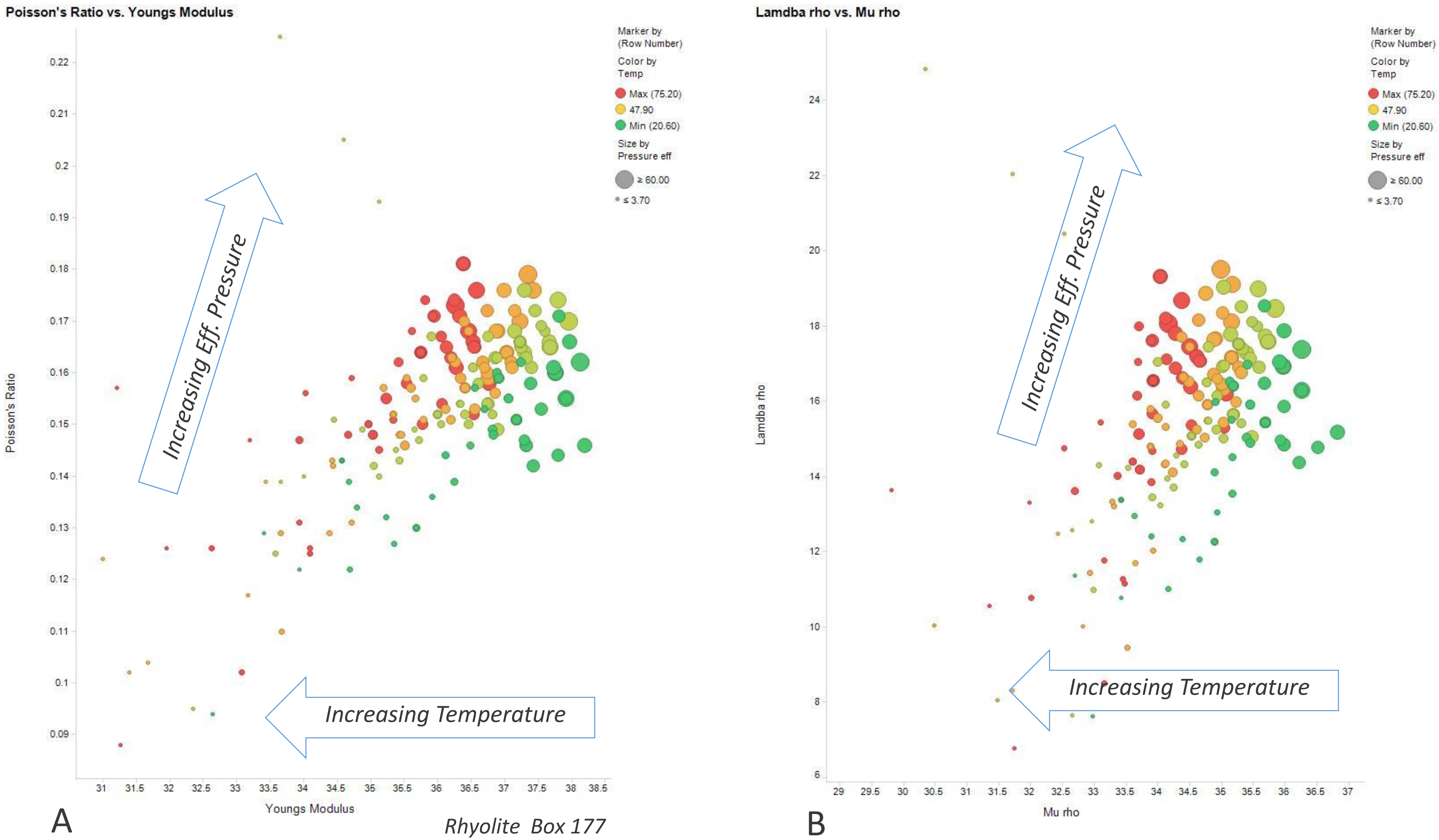
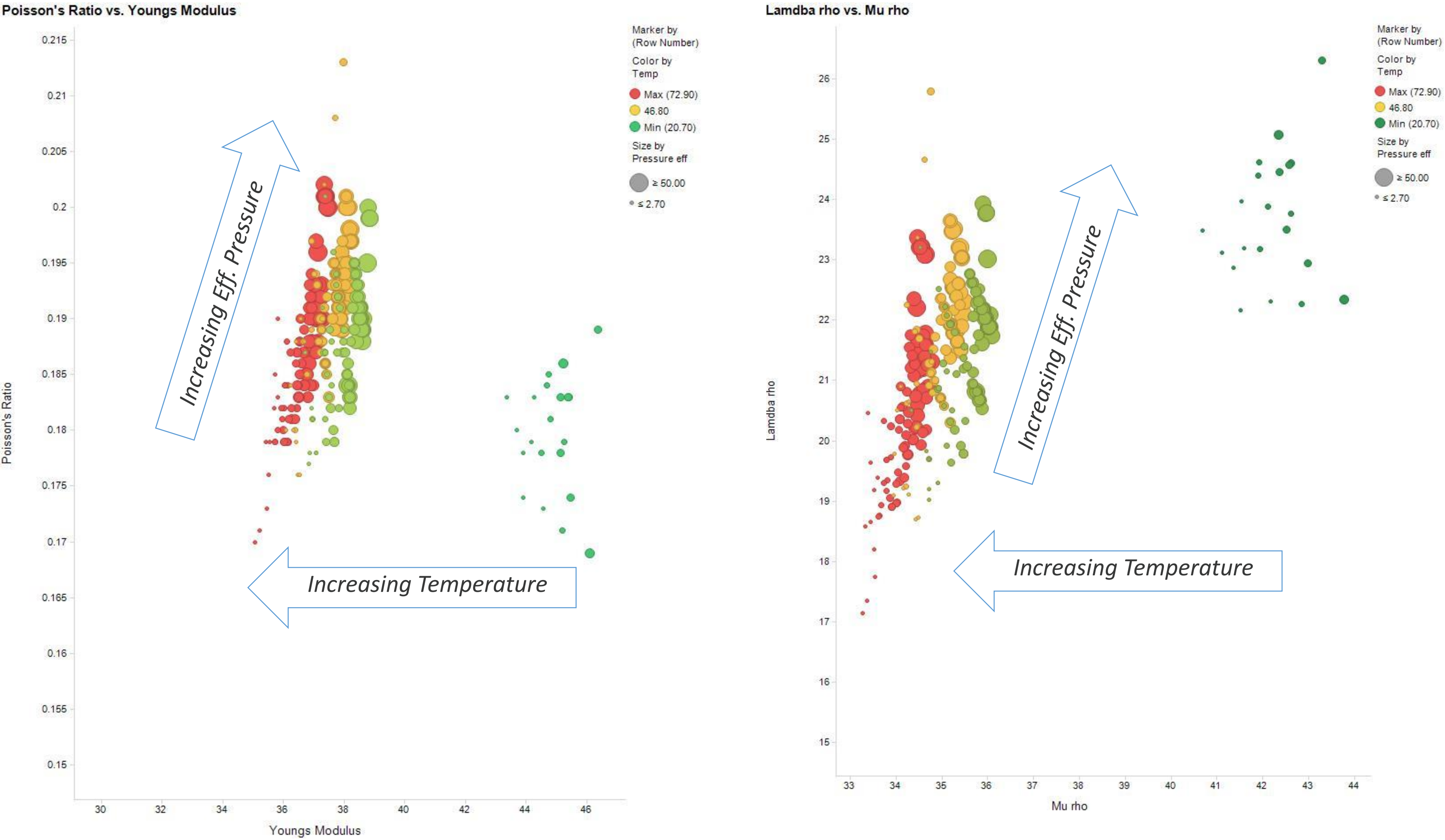

RhyoliteVp-Vs1
4000
3500
3000
2500
2000
1500
1000
500
0
Vs1 (m/s)
0
1000
2000
3000
4000
5000
6000
7000
Vp (m/s)
18
16
14
12
10
8
6
4
2
Porosity (%)

Figure 2



Interpretation Young's modulus versus Poisson's ratio and interpretation of λρ versus μρ moduli

Figure 5B



A

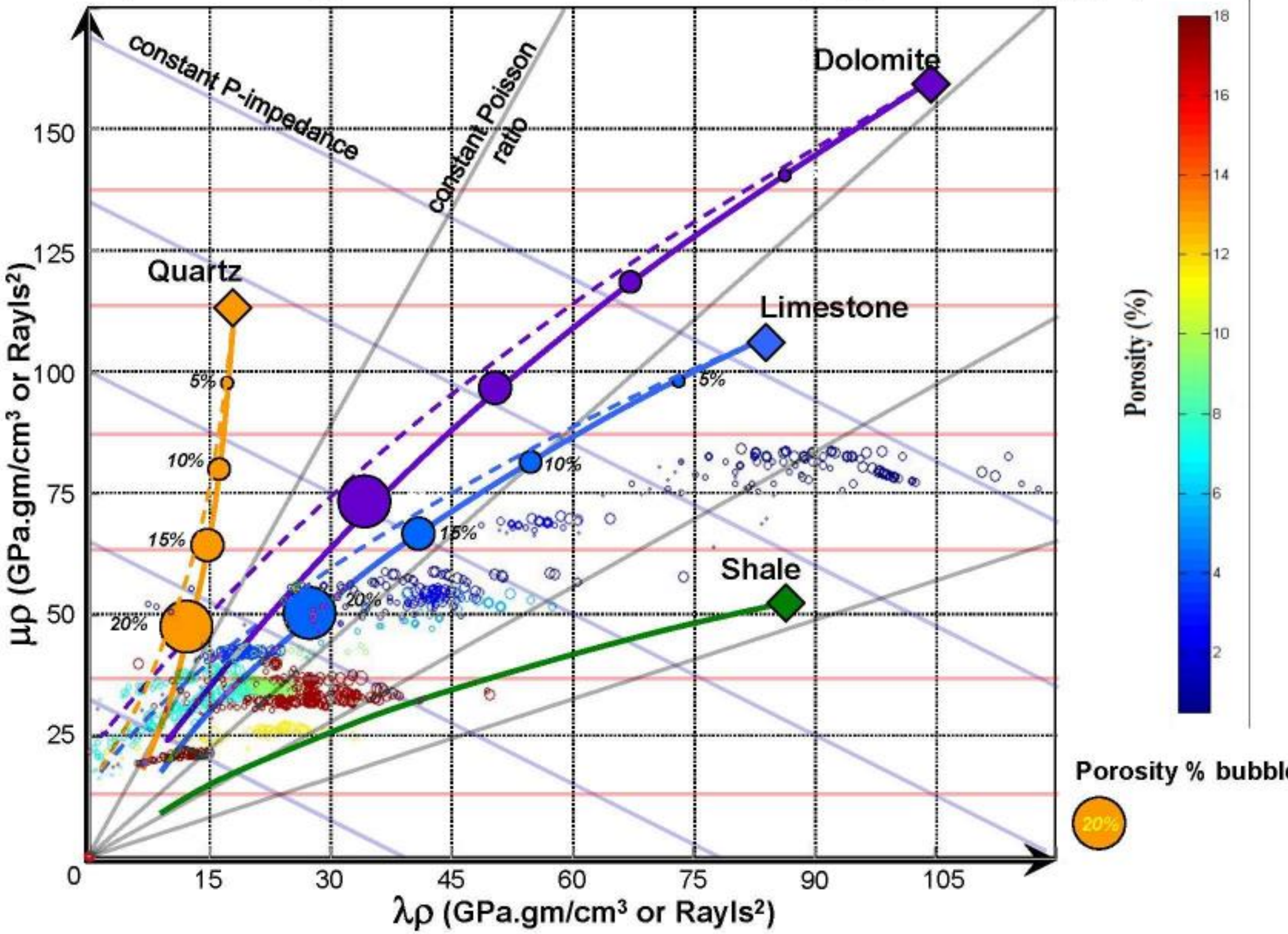
Rhyolite Box 154

B

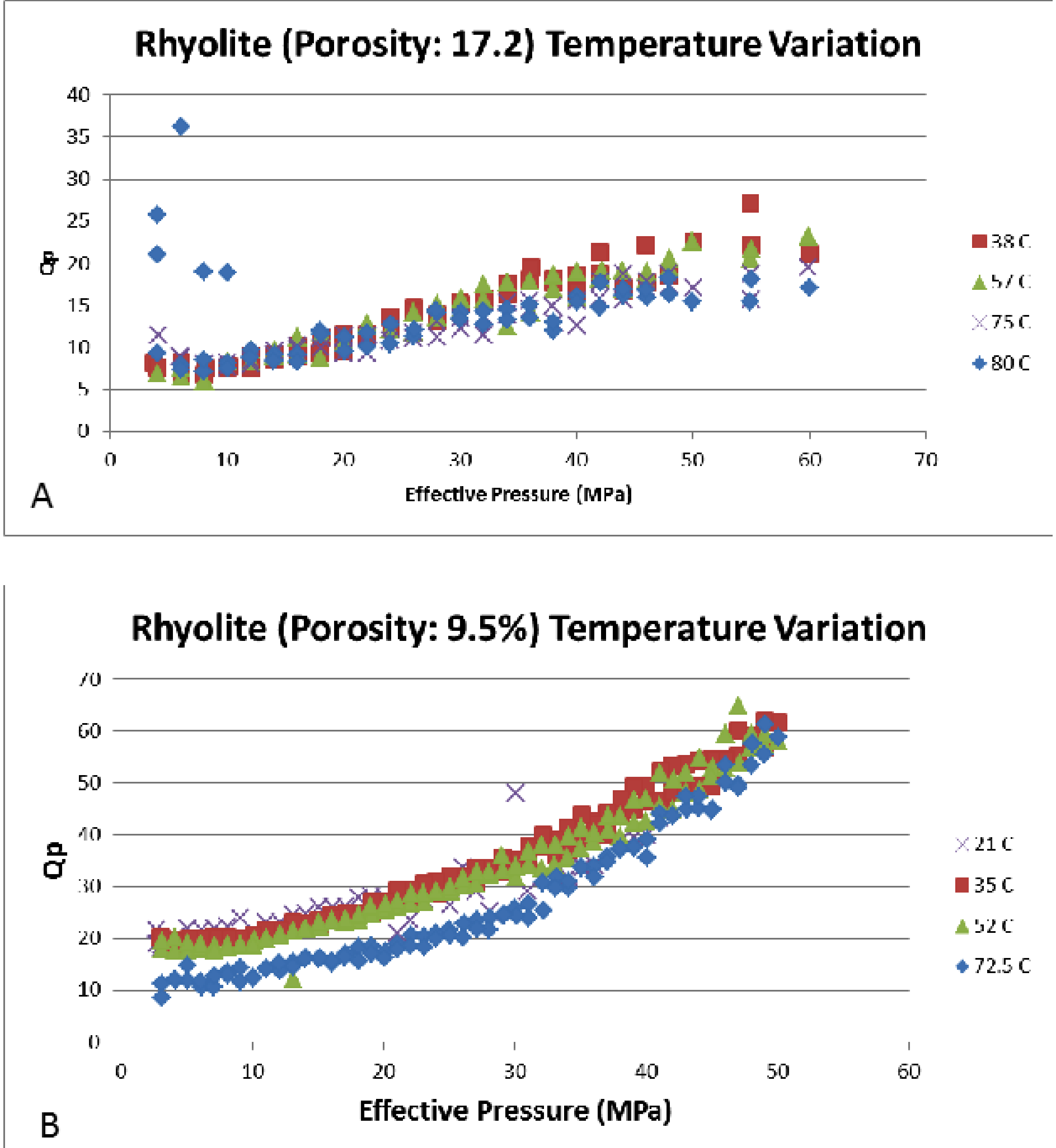
Interpretation Young's modulus versus Poisson's ratio and interpretation of λρ versus μρ moduli

Figure 5

Fluid, Porosity & Lithology directions in LambdaRho ($\lambda\rho$), MuRho ($\mu\rho$) space



(Adapted from Hoffe, Perez and Goodway
CSEG convention 2008)



Rhyolite (Porosity: 17.2) Temperature Variation
Qp
Effective Pressure (MPa)
38 C
57 C
75 C
80 C
A
Rhyolite (Porosity: 9.5%) Temperature Variation
Qp
Effective Pressure (MPa)
21 C
35 C
52 C
72.5 C
B

Figure 5

Conclusions

- In our experiments we observed that ultrasonic wave scattering due to heterogeneities in the carbonate samples was dominant.
- Although we observed lower $\mu\varrho$ values, trends in our data strongly agreed with the model proposed workers interpreting AVO trends in a LMR cross plot space.
- We found that $\mu\varrho$ was proportional to temperature while $\lambda\varrho$ was temperature independent and that $\lambda\varrho$-$\mu\varrho$ trends were extremely dependent on porosity.
- Higher porosity results in lower values for both $\lambda\varrho$ and $\mu\varrho$.
- The presence of fluids causes a distinct shift in $\lambda\varrho$ values, an observation which could provide insight into subsurface exploration using amplitude variation with offset (AVO) classification.

Thank you!
Acknowledgements

- This research was supported by the U. S. Department of Energy National Energy Technology Laboratory and was conduced in collaboration with the Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, and Lawrence Livermore National Laboratory. Dr. Greg N. Boitnott of NER was very helpful answering our endless questions regarding the AutoLab and associated operational parameters. We wish to thank Dr. Bob Hardage and Rebecca Symth of the Bureau of Economic Geology and the Southwest Regional CO_2 Partnership for their help and support in this project. Helpful discussions with Dr. Grant Bromhal and Dr. Robert Dilmore improved this research activity.

Static Moduli and Moduli Ratio Definitions in Lamé terms

Lamé parameters:

Rigidity Mu (μ) and "Pure Incompressibility" Lambda (λ)

Common moduli resulting from medium's measurement condition:

"Compressional P-wave Modulus" (Bound uni-axial compression) $M = \lambda + 2\mu$

Young's Modulus (Unbound uni-axial compression) $E = \mu(3\lambda+2\mu)/(\lambda+\mu)$ $E = M - 2\lambda\nu$

Bulk Modulus $K = \lambda + (2/3)\mu$ $K = M - (4/3)\mu$

- Poisson's ratio $\nu = \lambda/(2\lambda + 2\mu)$
- Vp/Vs ratio $\sqrt{(2 + \lambda/\mu)}$

A given material has various moduli that are purely a function of measurement conditions

Lamé parameters λ and μ are invariant and form the basic elements within moduli, giving a simpler physical meaning

This slide courtesy Bill Goodway: The Magic of Lamé

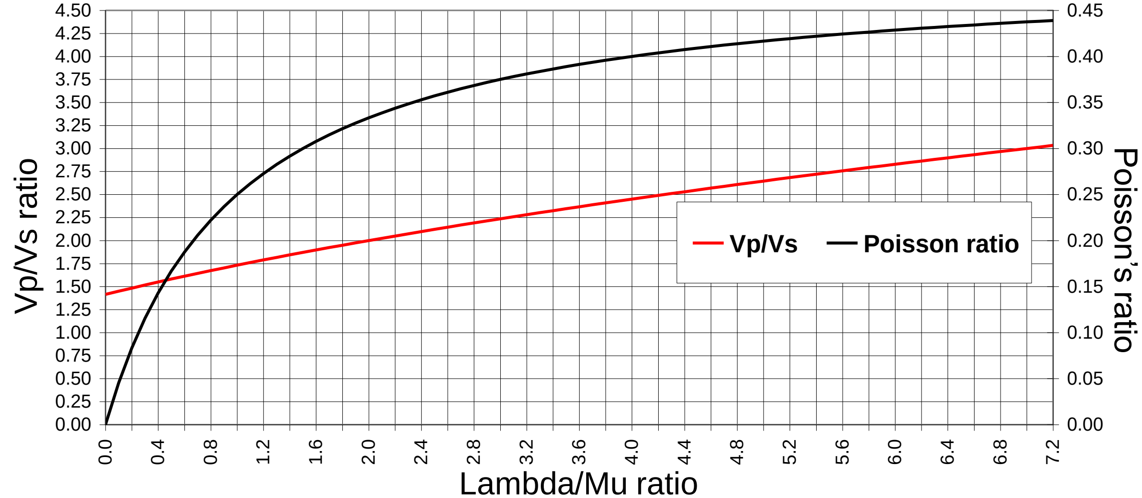
Sensitivity of Vp/Vs, Poisson's ratio vs. Lambda/Mu ratio

Comparison to Vp/Vs

$$\frac{d(Vp/Vs)}{d(\lambda/\mu)} = 0.5\left(\frac{Vp}{Vs}\right)^{-1}$$

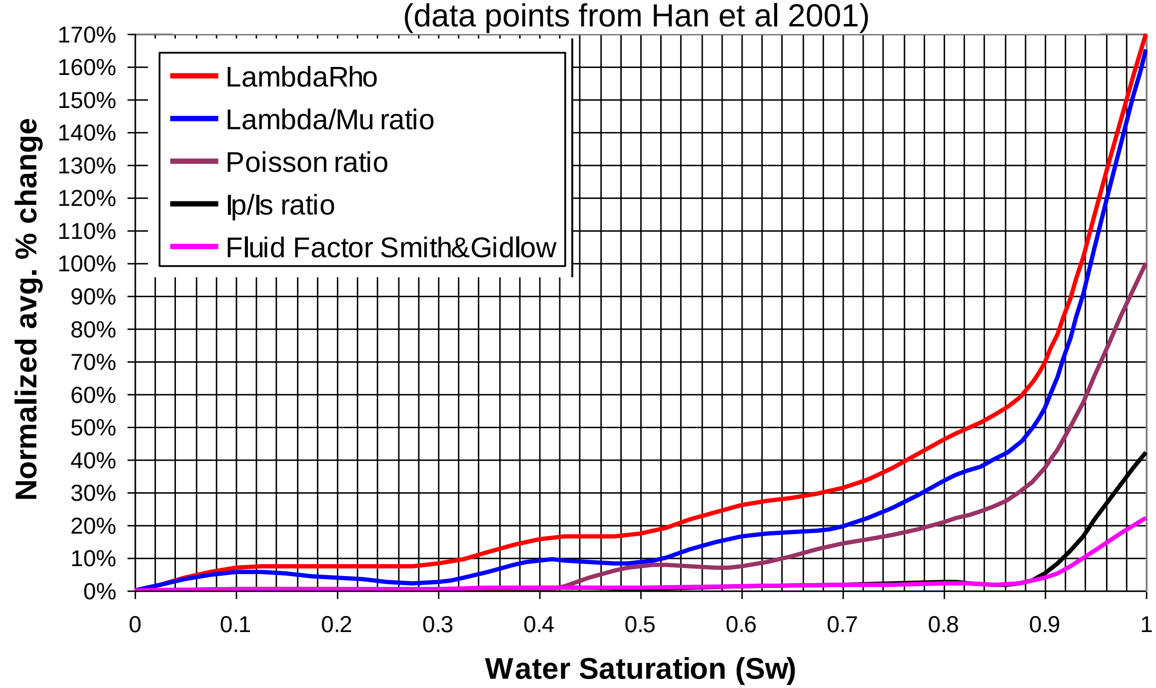
Comparison to Poisson's ratio

$$\frac{d\nu}{d(\lambda/\mu)} = 0.5(1-2\nu)^2$$



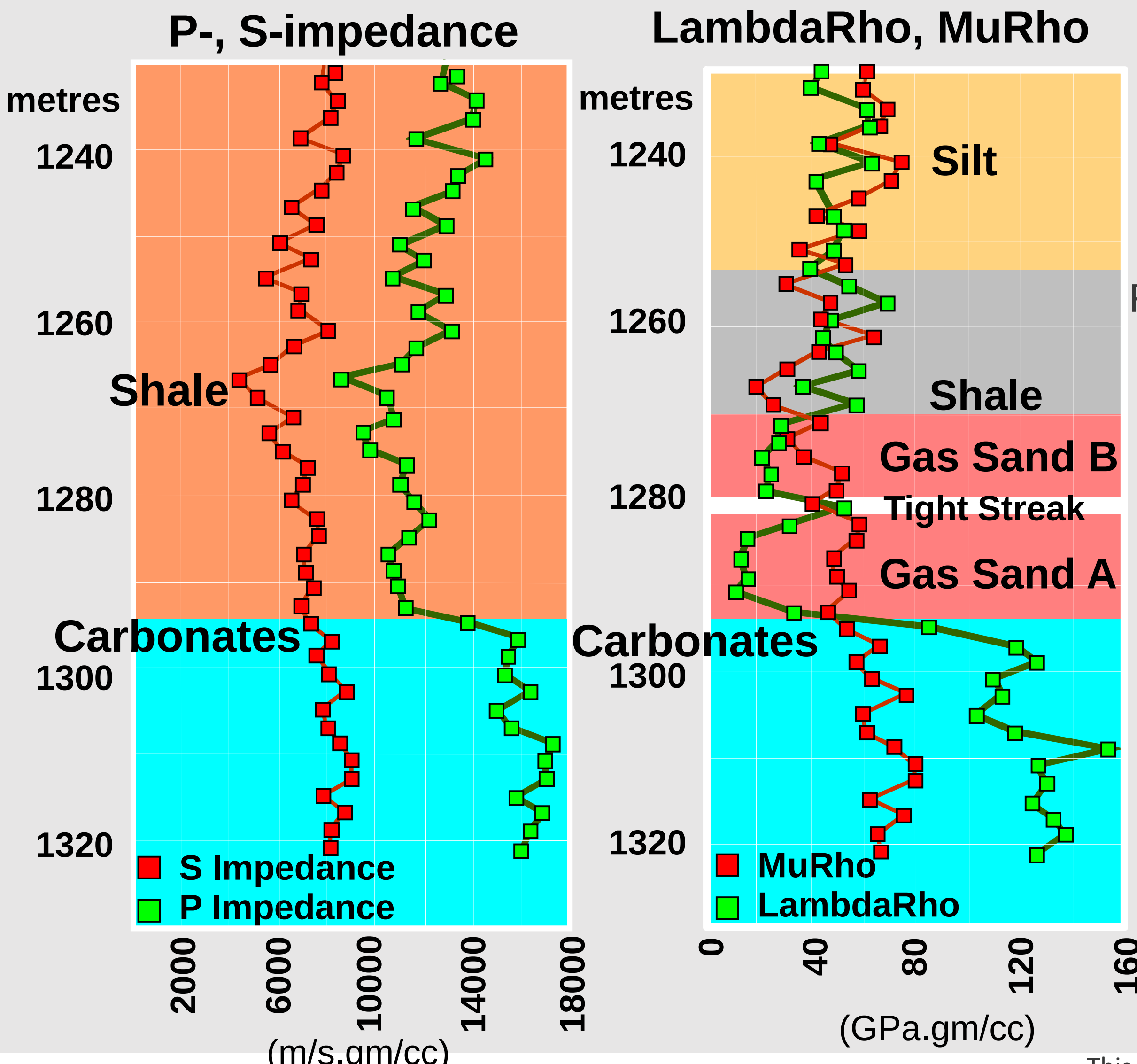
Relative sensitivity to water saturation:
Ip/Is, Poisson's, Lambda/Mu ratios
and LambdaRho, "Fluid Factor"

"Fizz Water" (Low Gas Saturation) Discrimination
(data points from Han et al 2001)



This slide courtesy Bill Goodway: The Magic of Lamé

Log tracks for Sands, Shales and Carbonates showing improved LambdaRho, MuRho crossover discrimination of gas zones and lithologies compared to P-, S-impedance



Impedance = Velocity$*$Density

P-impedance = $V_p * \rho$

S-impedance = $V_s * \rho$

Relations to transform impedances to Lamé parameters $\lambda\rho$, $\mu\rho$

$$\lambda\rho = (V_p * \rho)^2 - 2\,(V_s * \rho)^2$$

$$\mu\rho = (V_s * \rho)^2$$

This slide courtesy Bill Goodway: The Magic of Lamé